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The Proceedings

OF

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FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

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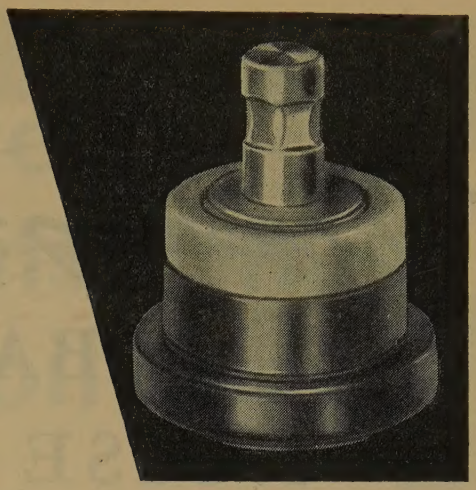
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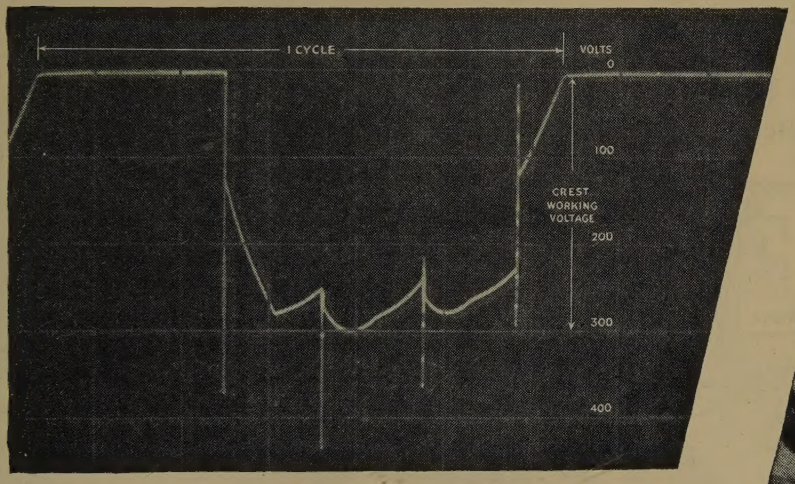
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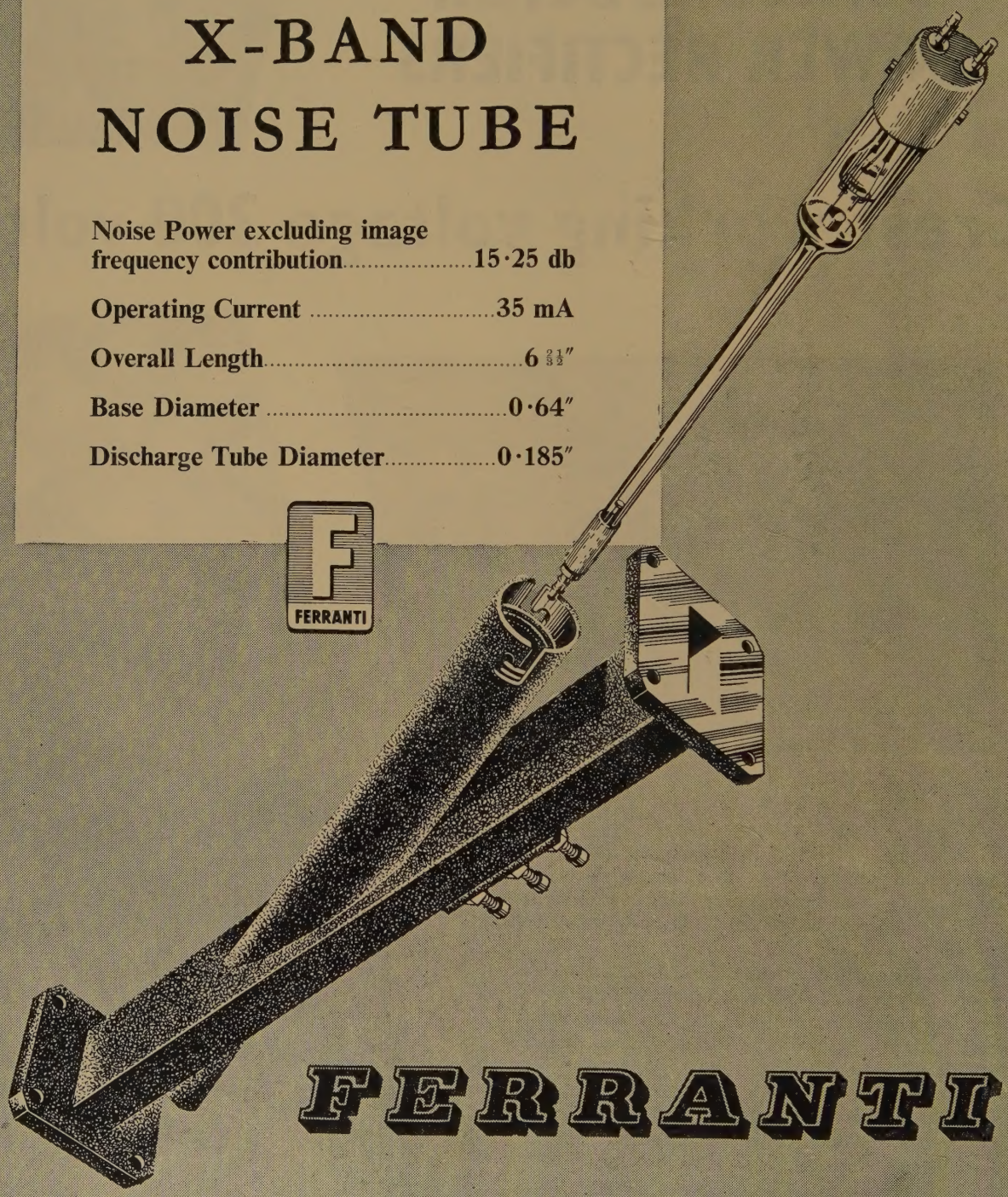
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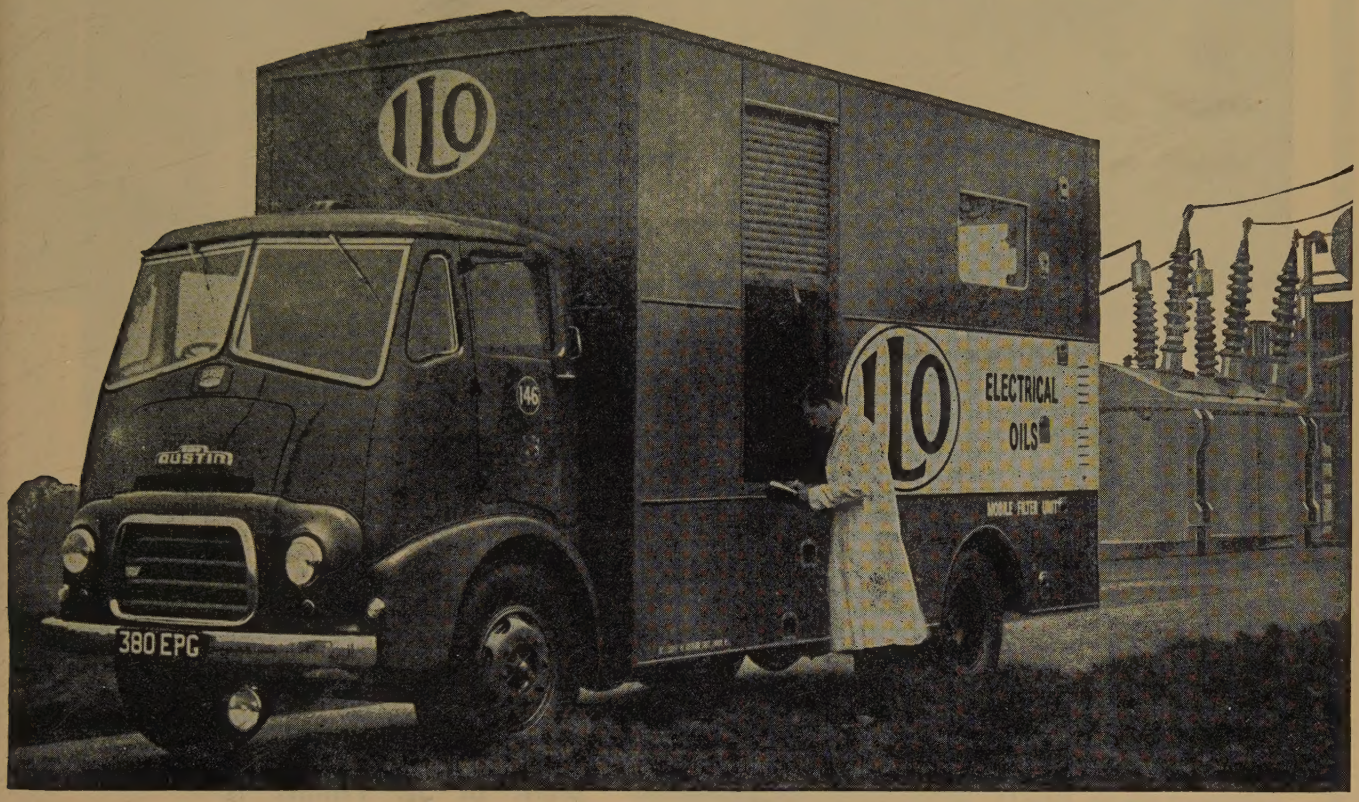


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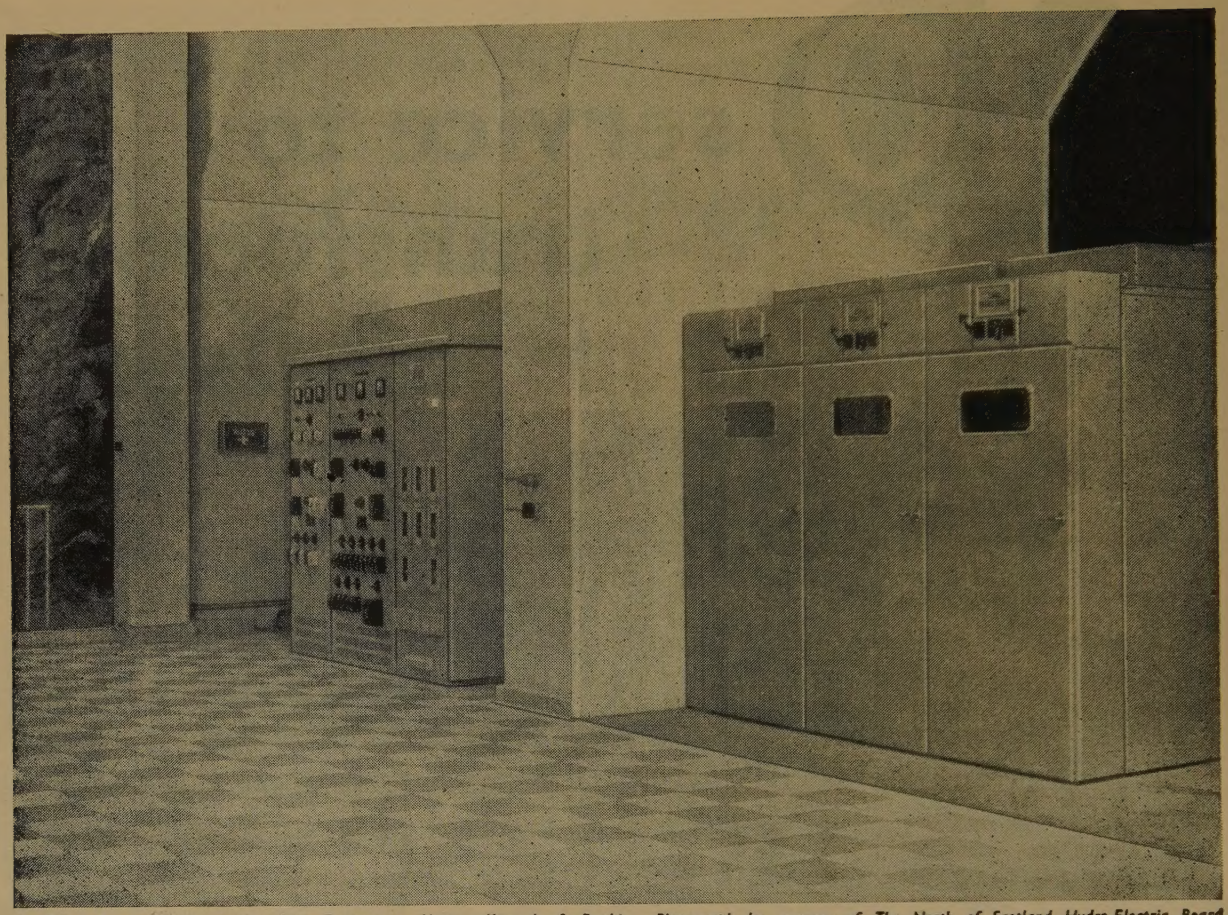


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St. Fillans Power Station. Consulting Engineers: Messrs. Kennedy & Donkin. Photograph by courtesy of The North of Scotland Hydro-Electric Board

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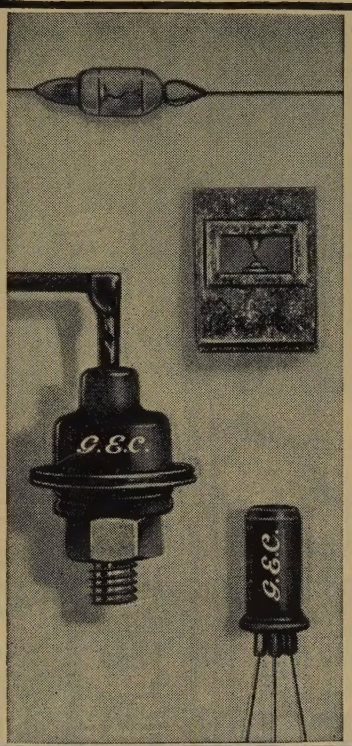
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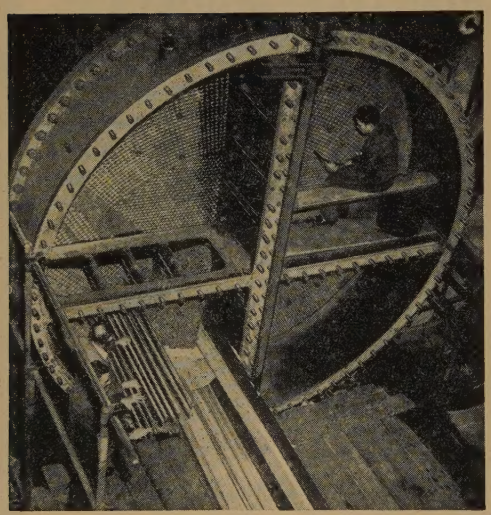
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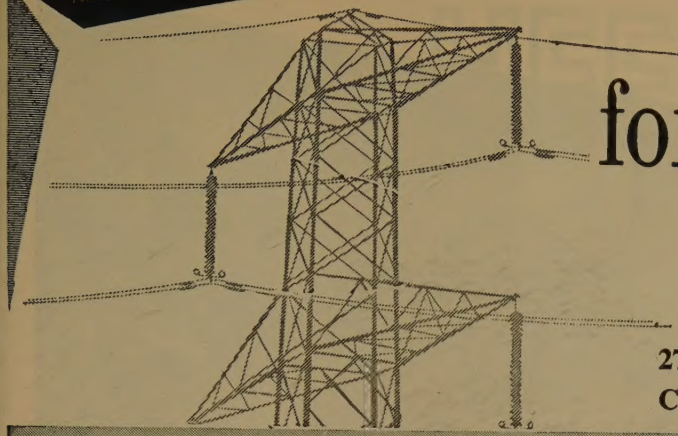
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Retubing a main condenser with thirty-five tons of SERCK Aluminium Brass condenser tubes at Deptford West Power Station.

Photo by courtesy of the Central Electricity Authority.

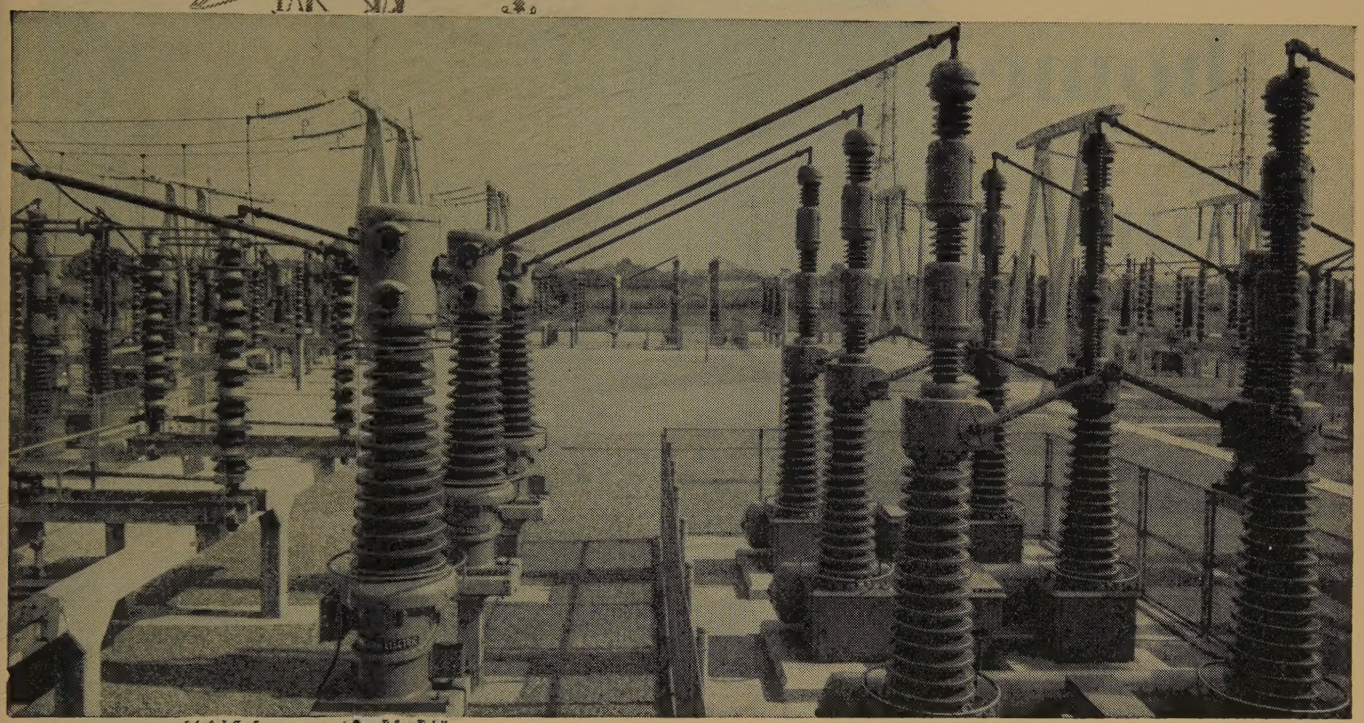


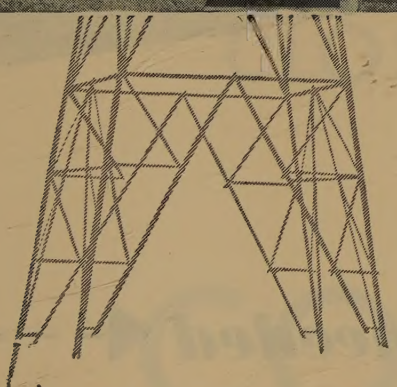
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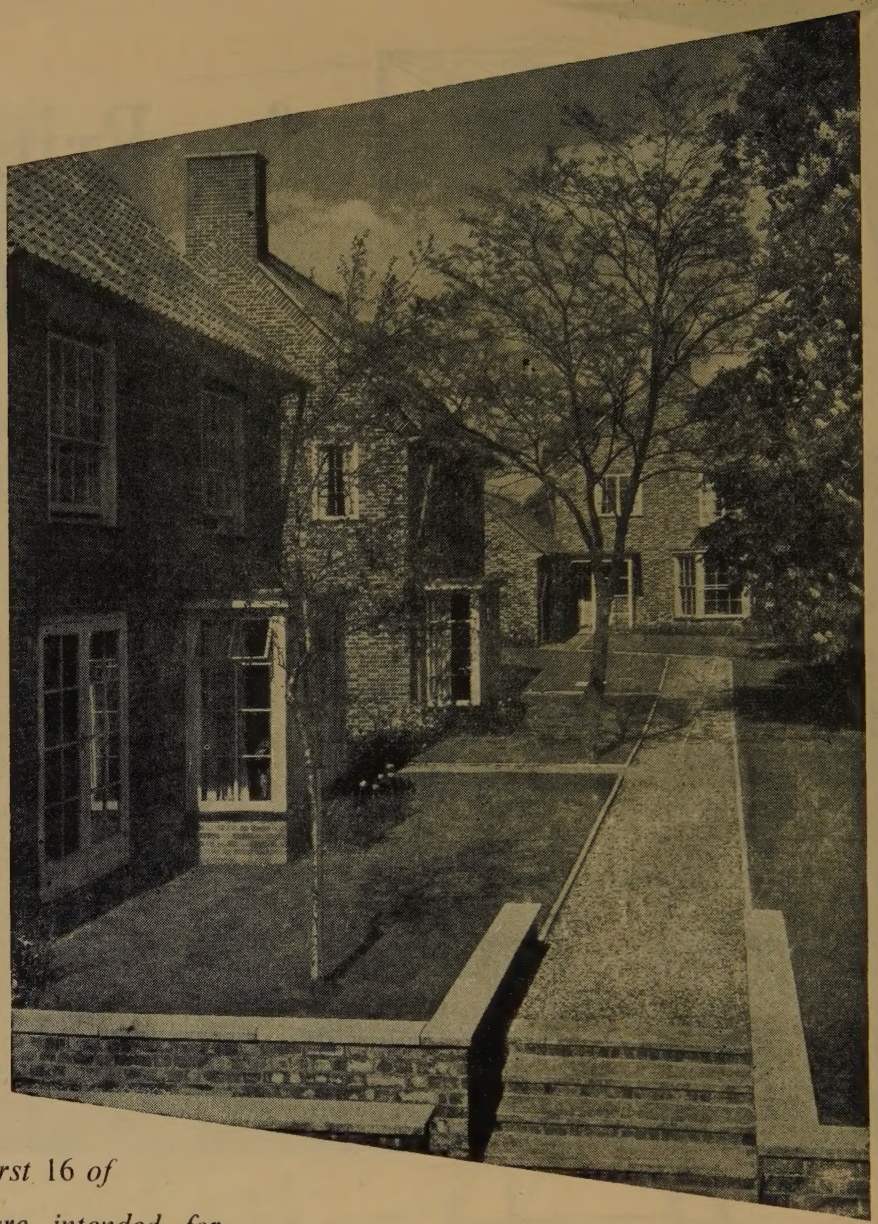
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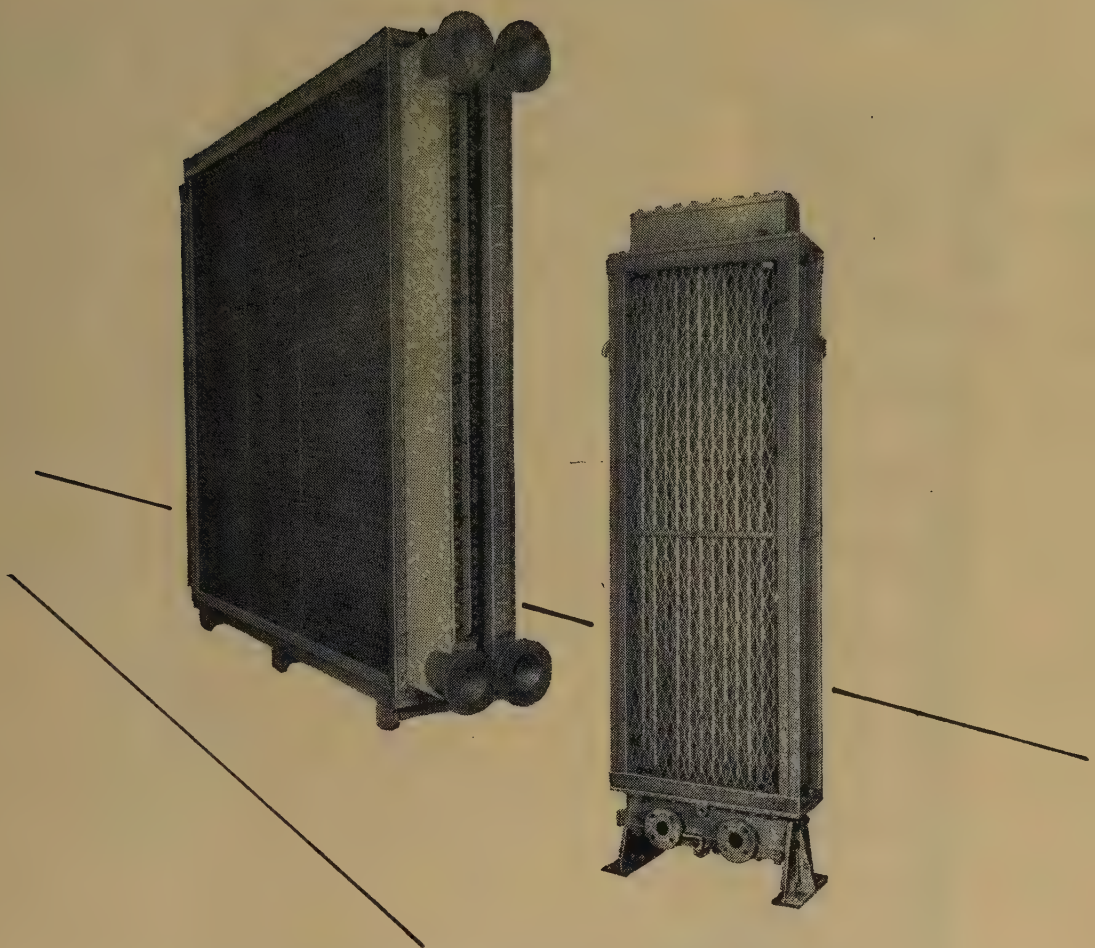
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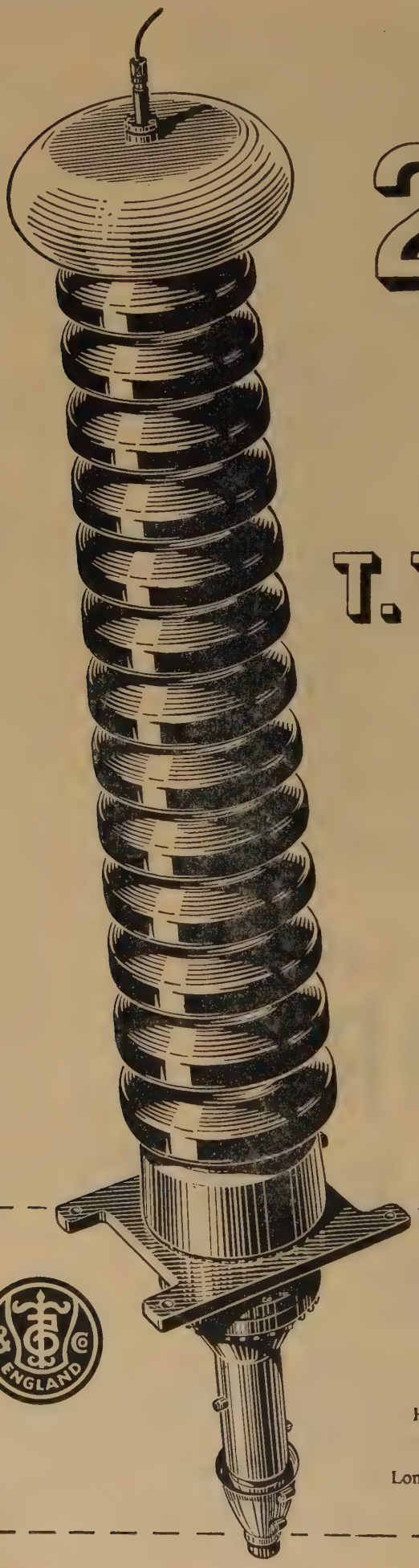


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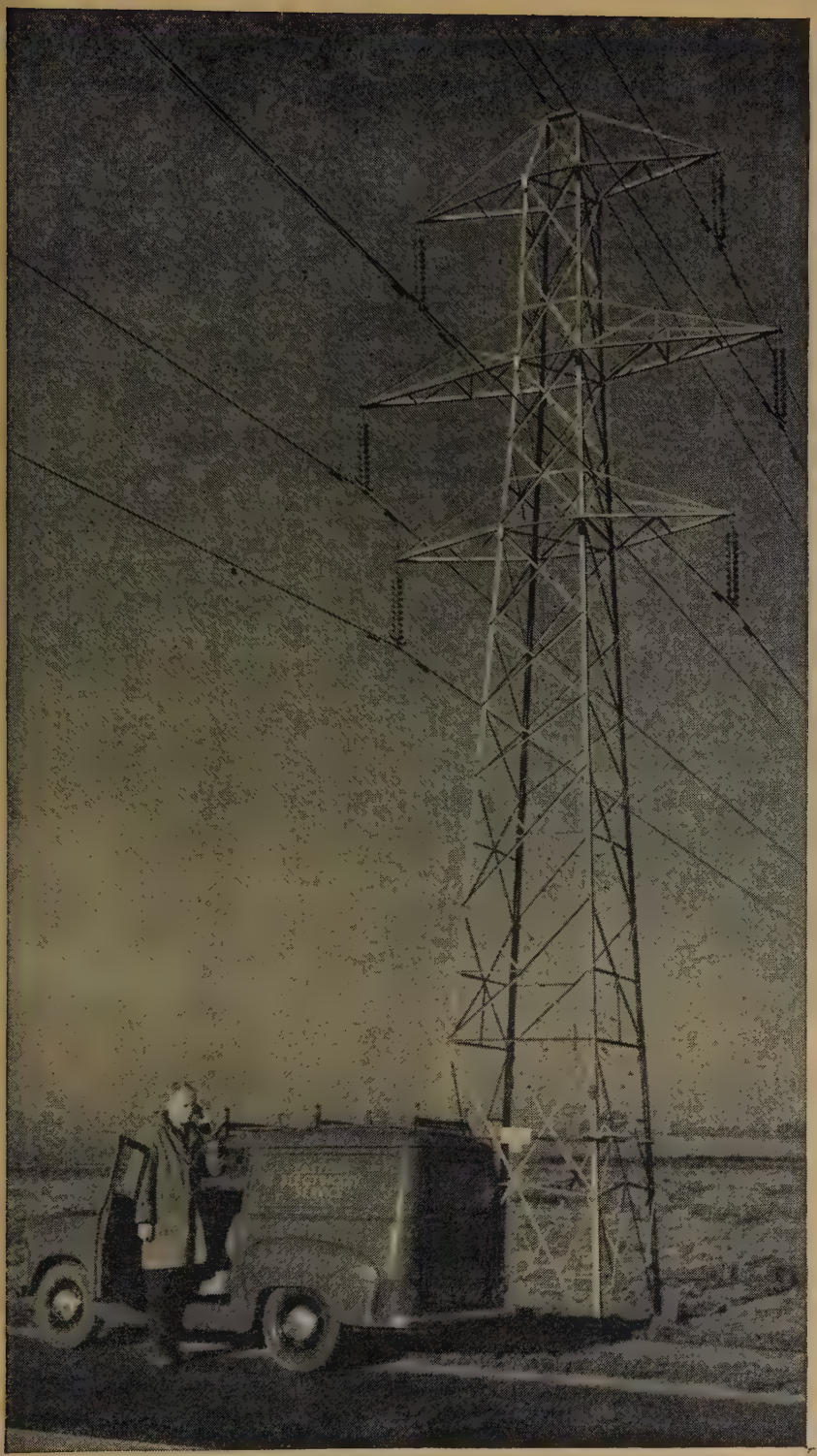
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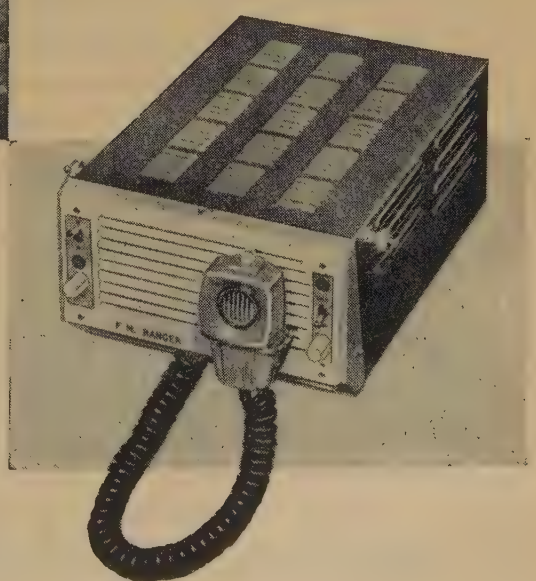


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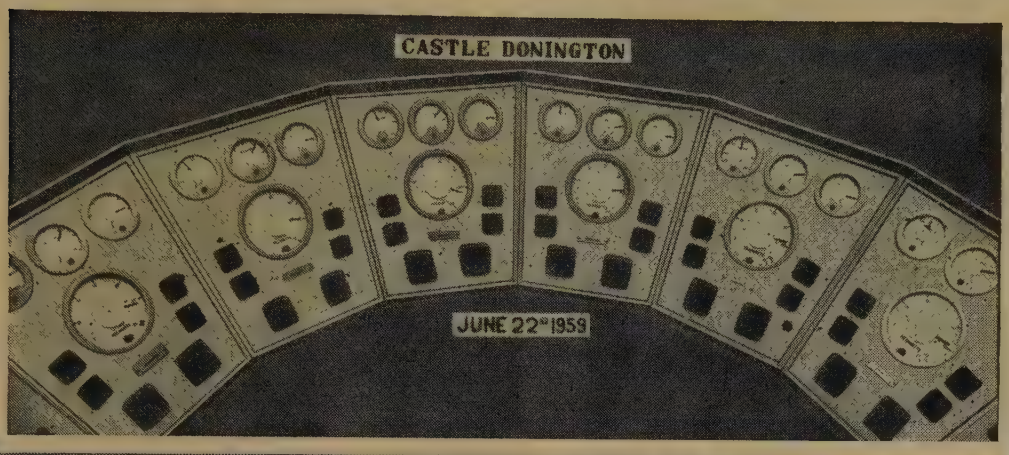
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Right: Photograph showing megawattmeters at Castle Donington in June 1959, registering unit outputs of approximately 102, 100, 102, 99, 98, 99 megawatts.

102 100 102 99 98 99

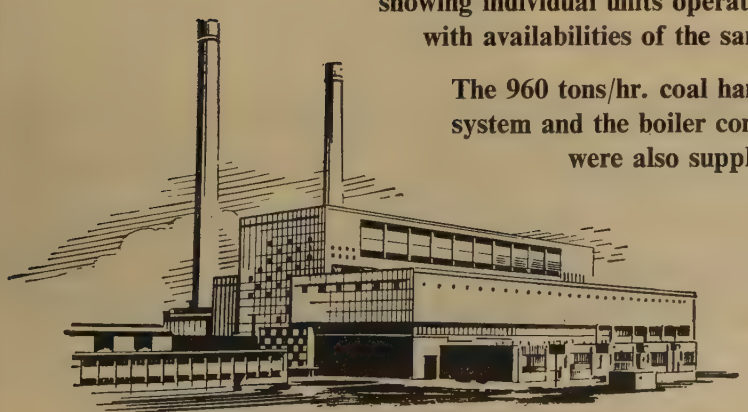
MEGAWATTS

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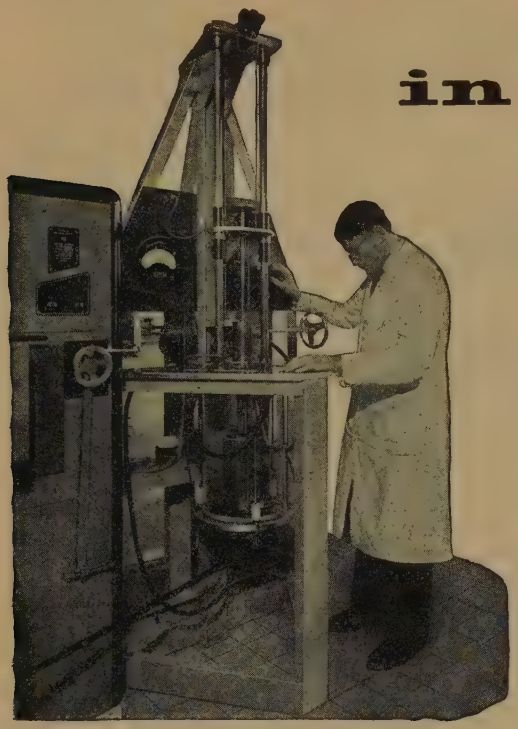
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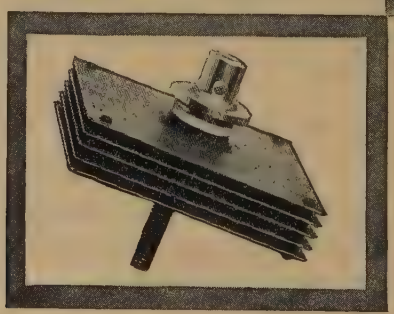
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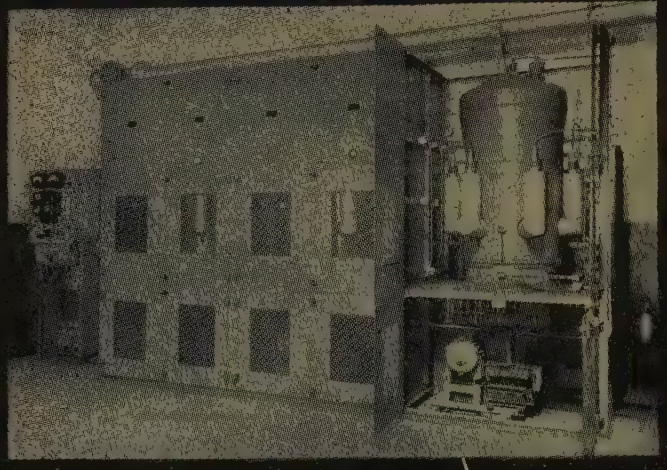


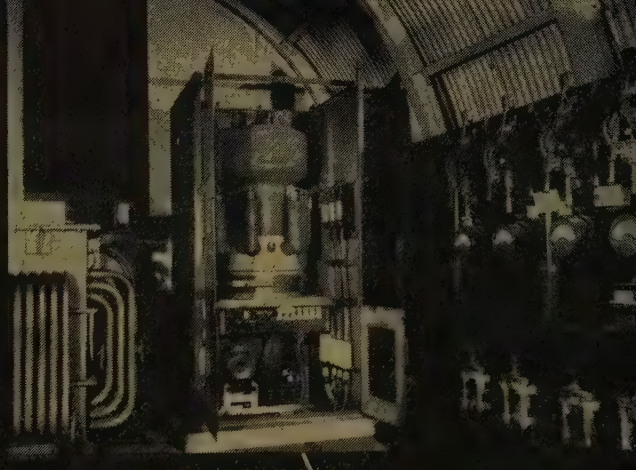
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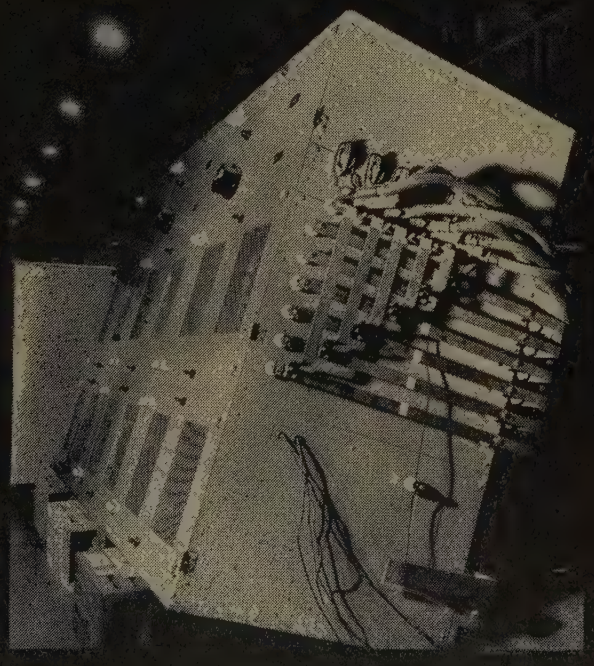




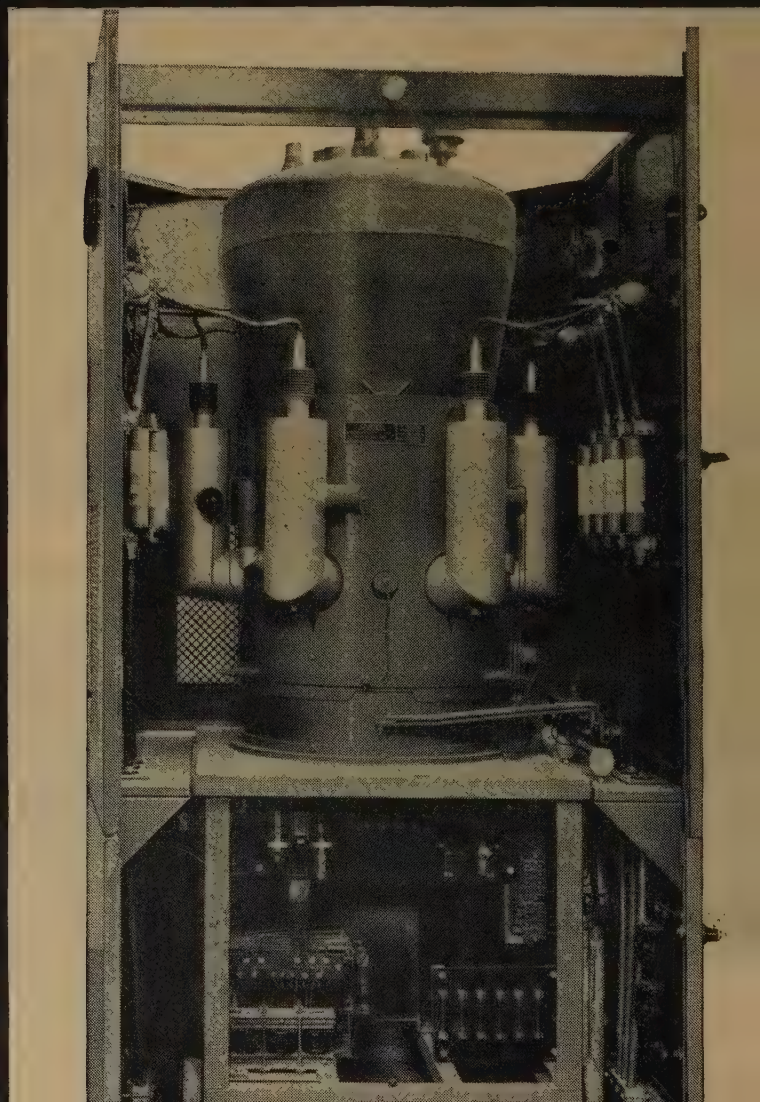
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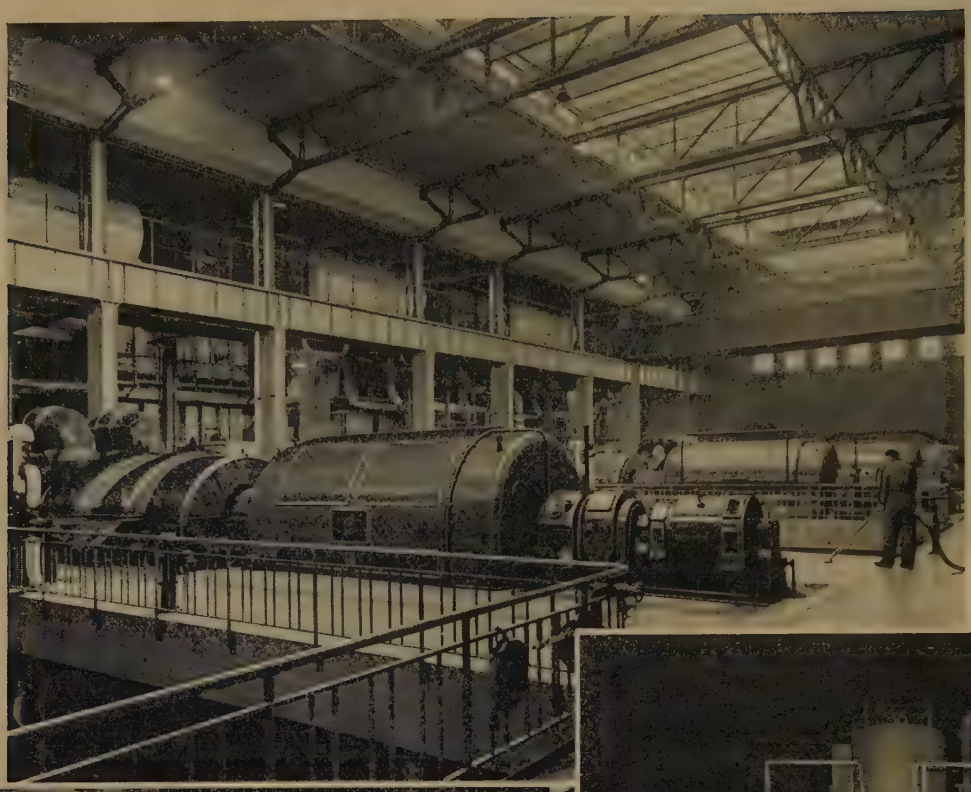
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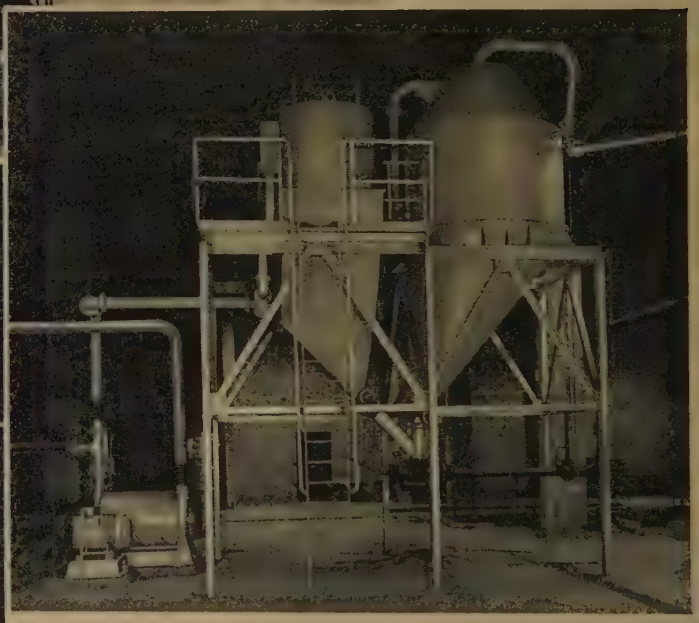
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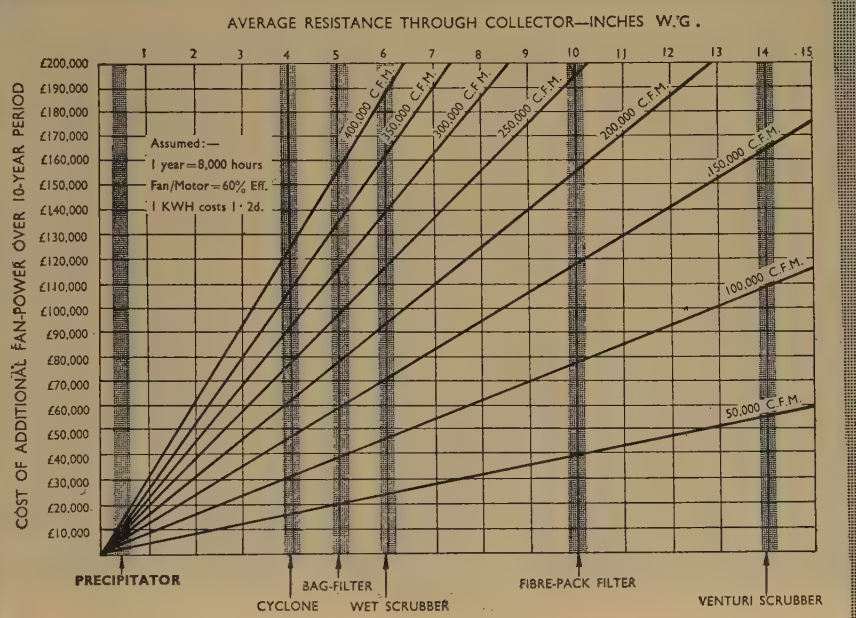
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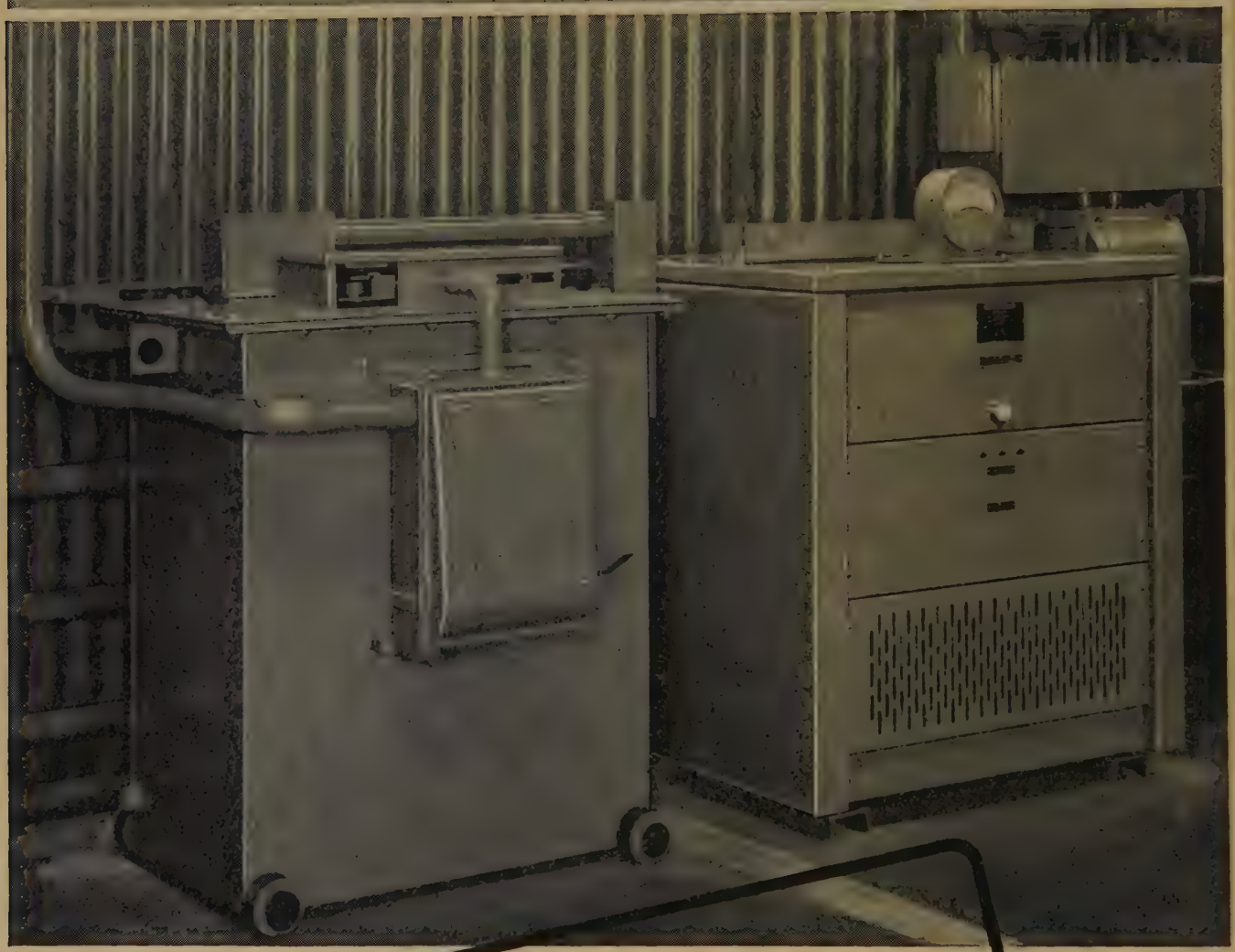
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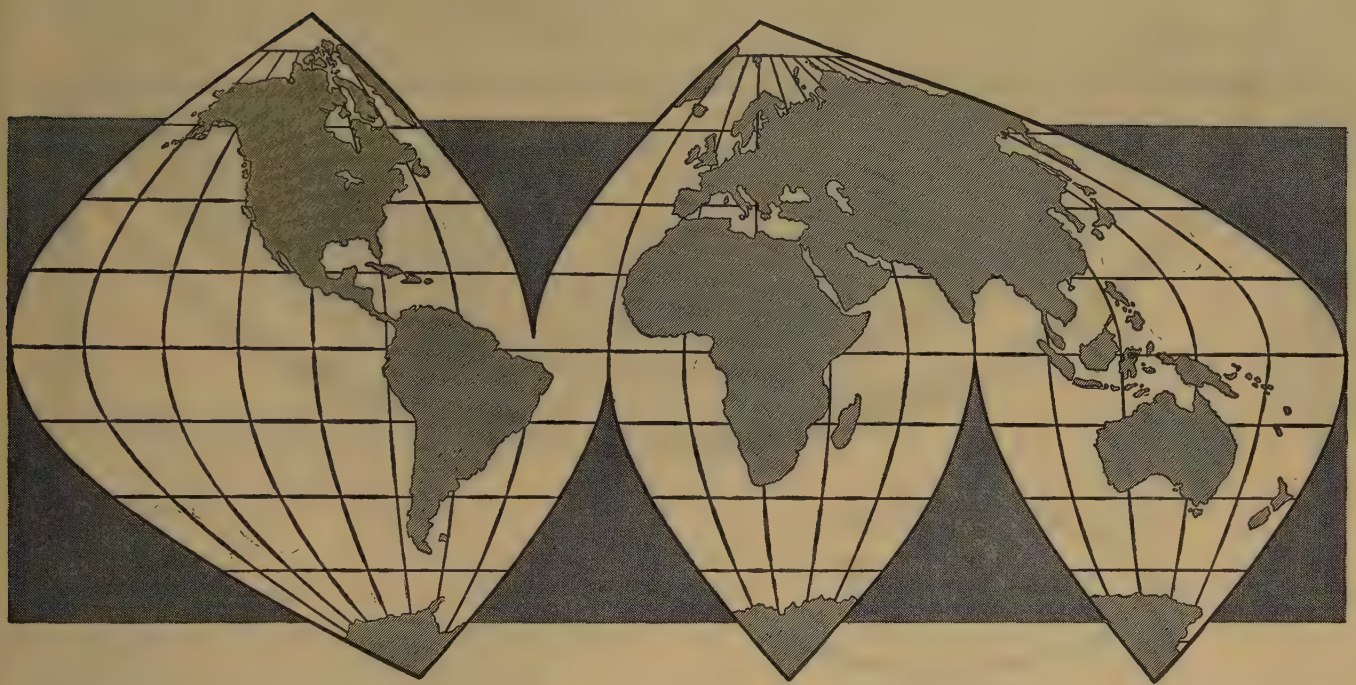
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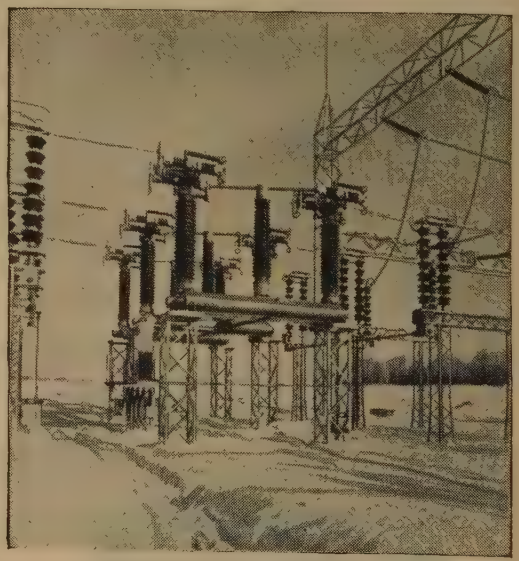


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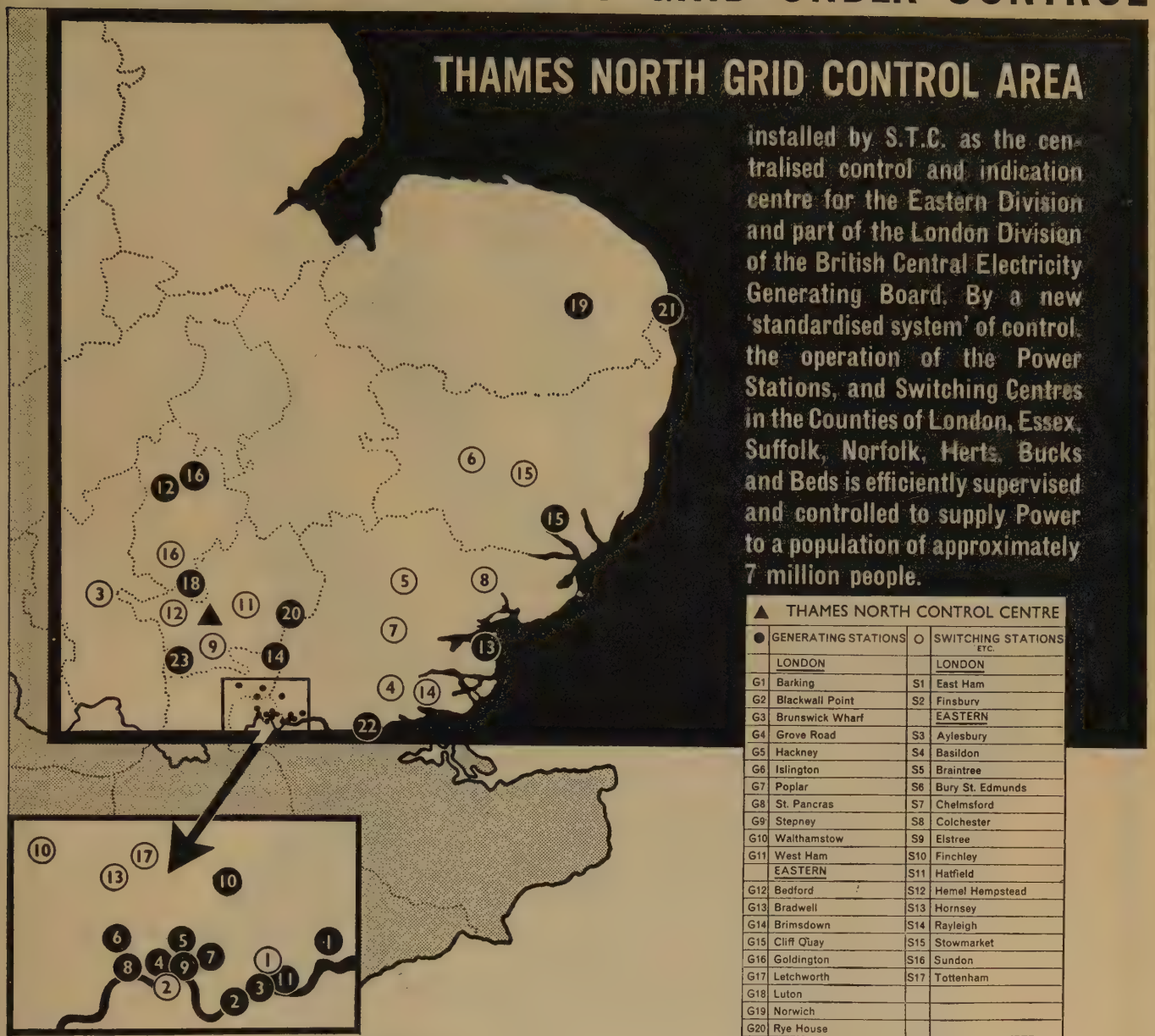
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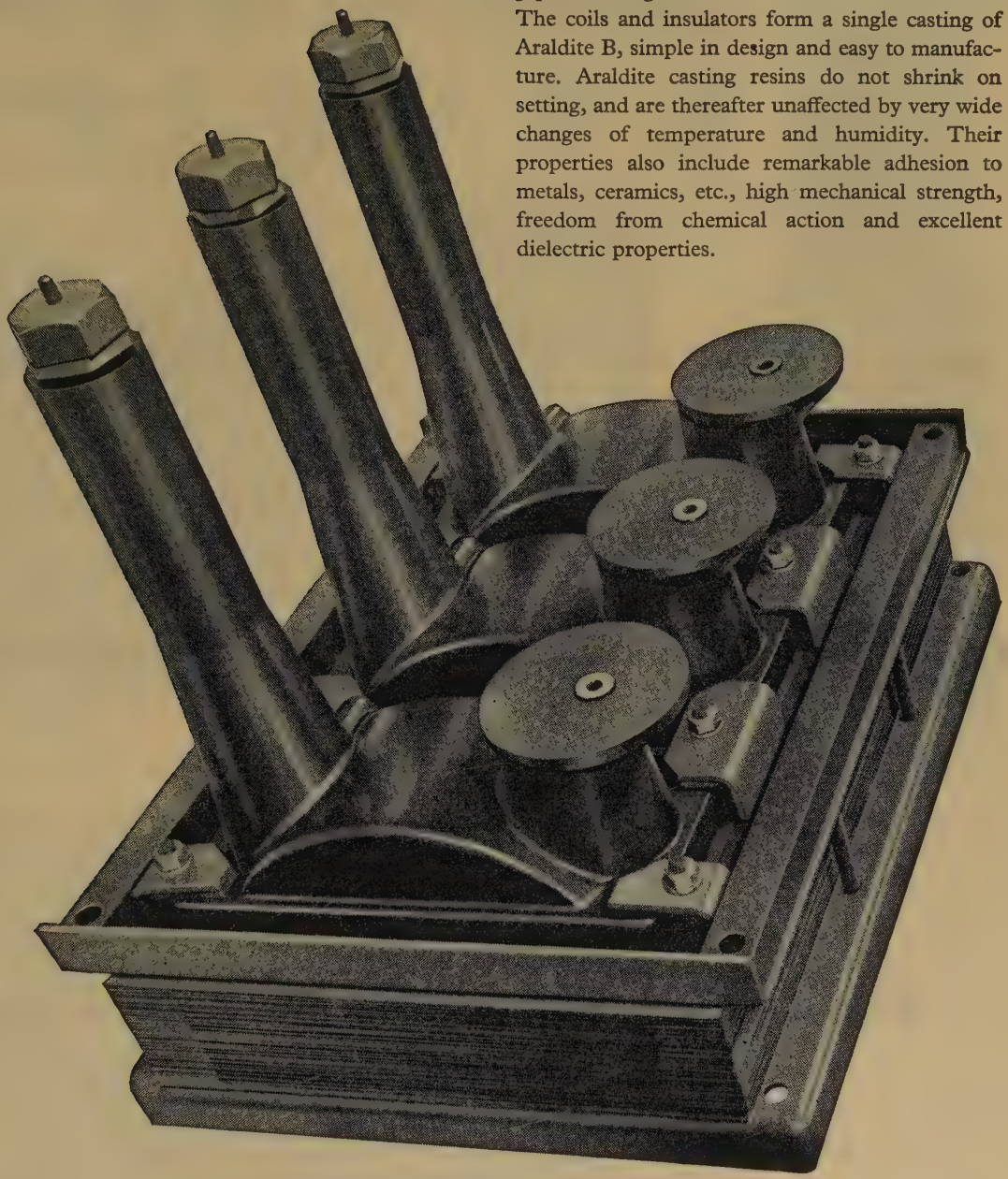
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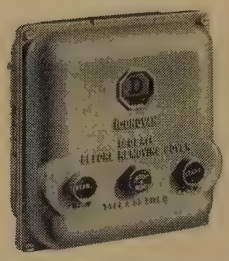


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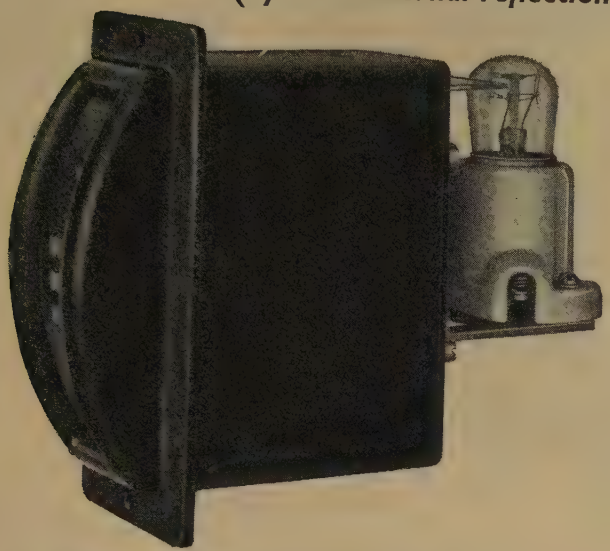
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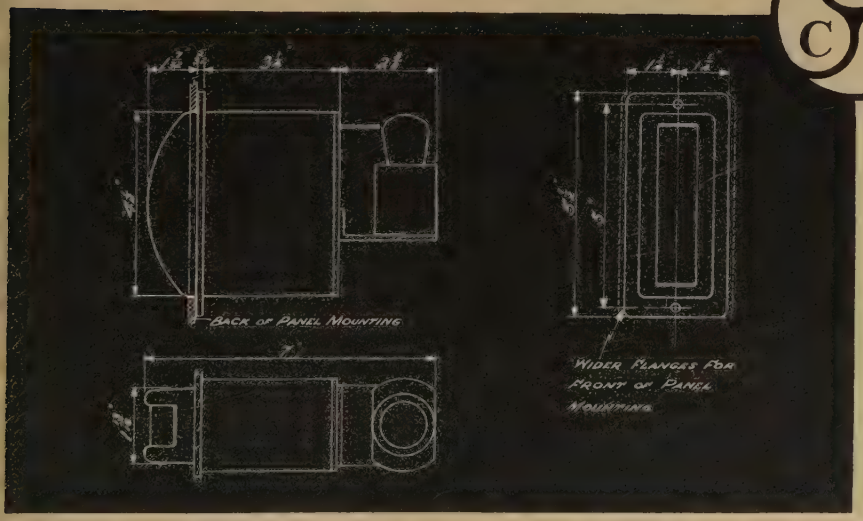
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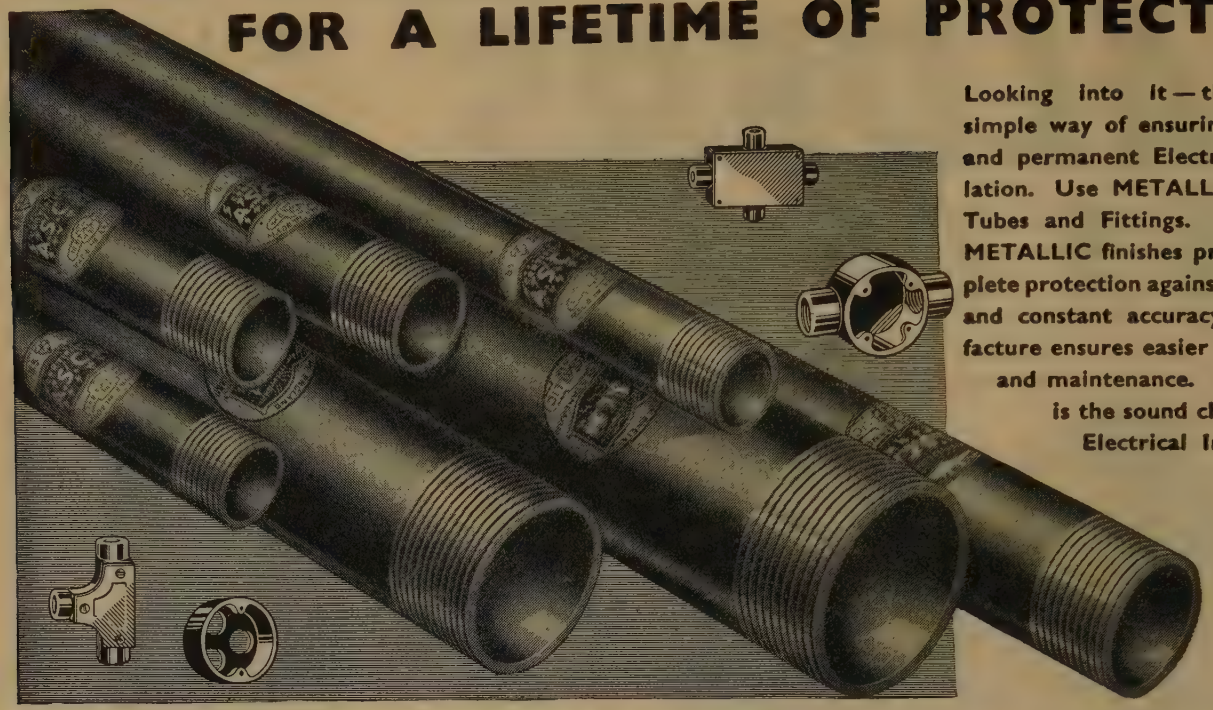
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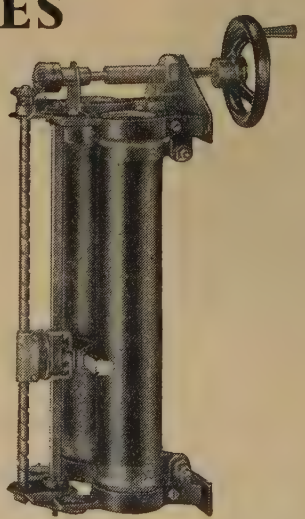
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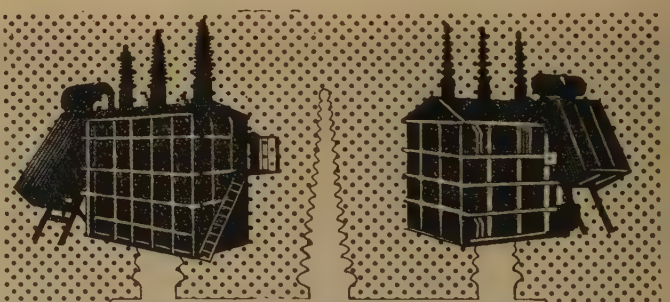
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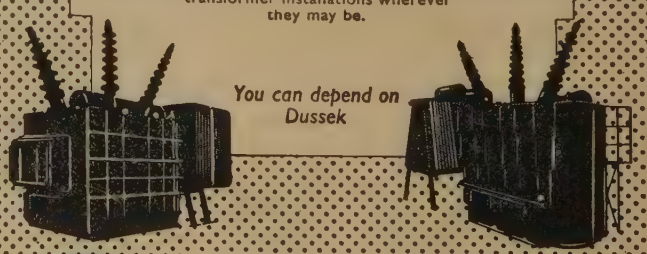
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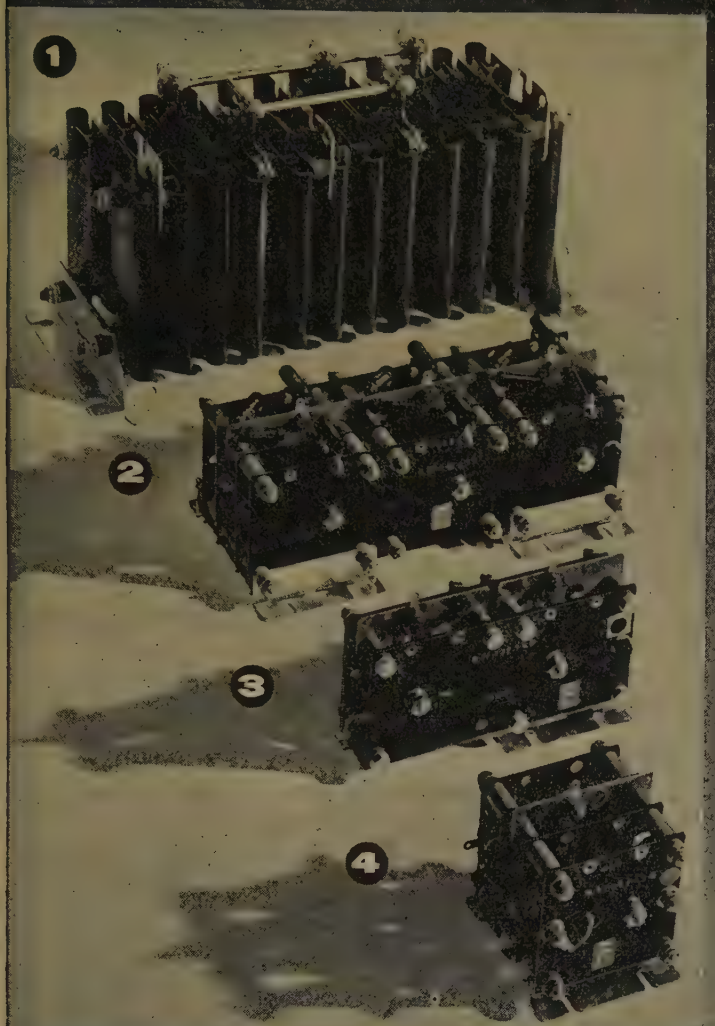
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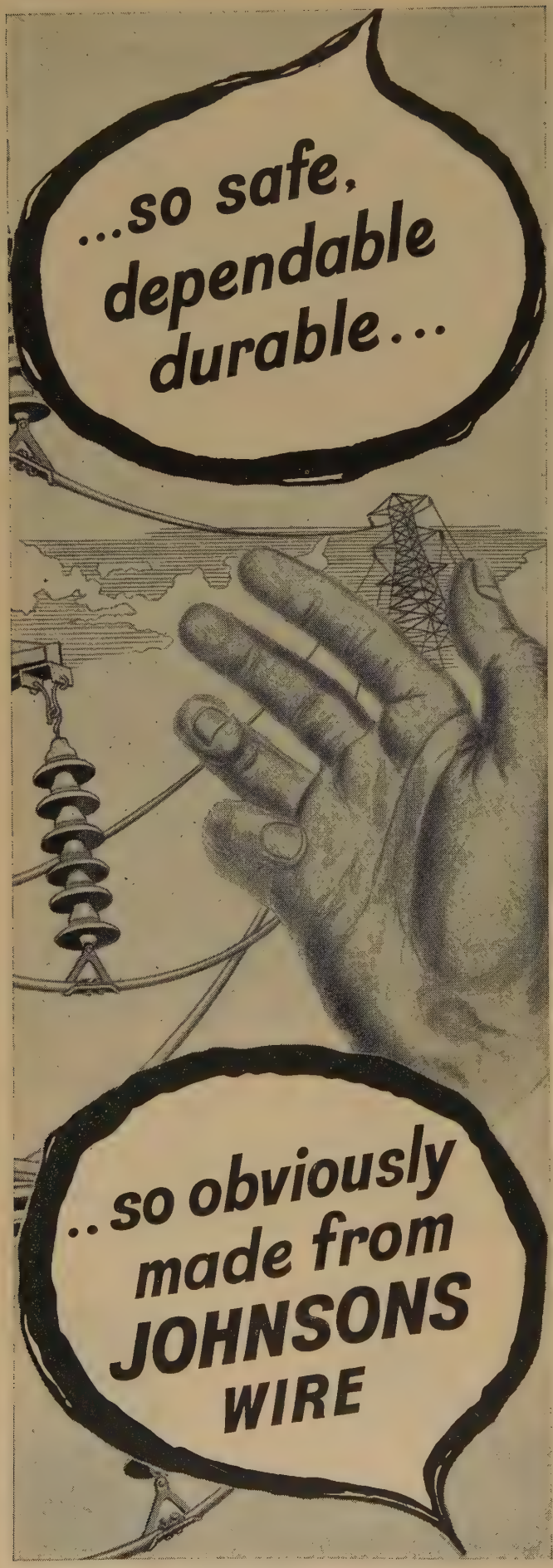
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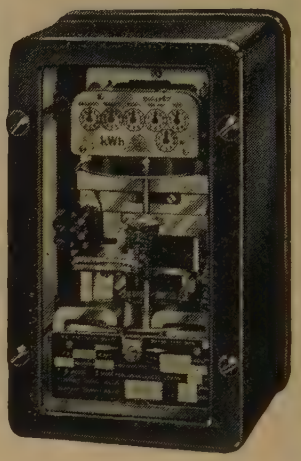


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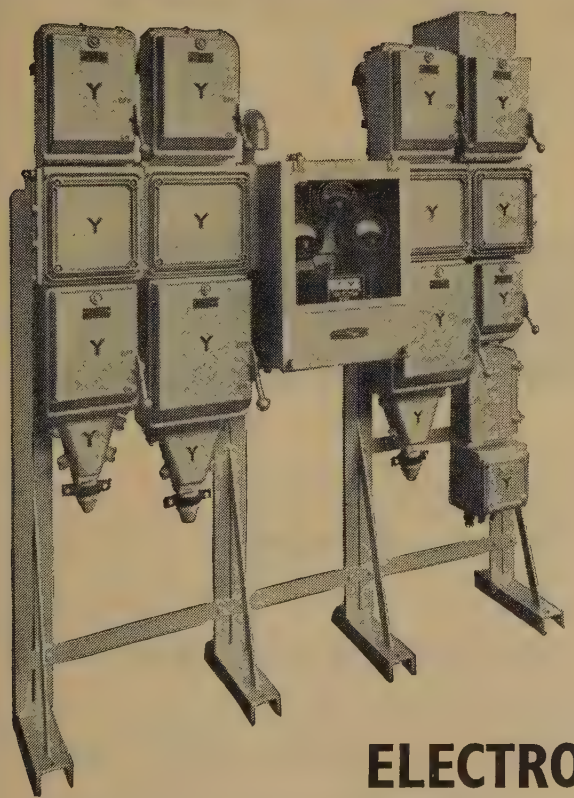
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ENGINEERING EDUCATION AT THE TECHNICAL UNIVERSITIES IN WESTERN GERMANY

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(*The paper was first received* 23*rd December*, 1958 *and in revised form* 31*st January*, 1959. *It was published in May*, 1959, *and was read before a joint meeting of* THE INSTITUTION OF ELECTRICAL ENGINEERS *and* THE INSTITUTION OF MECHANICAL ENGINEERS 28*th May*, 1959.)

(1) INTRODUCTION

This paper is based on a report submitted to the Lord President of the Council and to the Secretary of State for Foreign Affairs at whose suggestion and under whose auspices the team visited Germany in order to attempt to establish a comparison between the academic levels achieved in higher engineering education in Great Britain and in Western Germany. A complementary report has been prepared by a similar German team who visited England in July, 1958. The field of investigation was deliberately limited to the teaching of mechanical and electrical engineering at the Technische Universität, Berlin, and the Technische Hochschulen at Munich and at Aachen. (We refer to all three institutions as technical universities.) The report sketches in the general background, since without it the conclusions would be meaningless, and an attempt has been made to separate the opinions formed and conclusions reached from the facts which were ascertained.

Terminology

It is very difficult to write accurately when concepts which occur in one language do not exist in the other. Where essential, the German word has been inserted in parentheses, but in general this has been avoided at the expense of some loss in precision. In general, 'Western Germany' is abbreviated to 'Germany'.

(2) FACTUAL INFORMATION

(2.1) Background

Engineering education at university level in Germany takes place at the Technical Universities of Aachen, Berlin, Brunswick, Darmstadt, Hanover, Karlsruhe, Munich and Stuttgart, any of which might loosely be compared with the Imperial College of Science and Technology, University of London. These developed in the 19th century from existing technical schools and colleges; the German universities did not create faculties of engineering, as did British universities. A number of the technical universities, notably Berlin, have added arts faculties, and one or two universities are considering the addition of faculties of engineering.[2]

Although the developments in teaching of engineering in the two countries were contemporary, Germany produced a very much higher proportion of graduate engineers between 1900 and 1939 than did Britain. Today the proportions appear to be similar; in the academic year 1956–57 the numbers of engineering graduates in Germany were 1200 in mechanical engineering (including chemical engineering), 770 in electrical engineering, and 680 in civil engineering.[1]

(2.2) Structure of the Technical Universities

With the exception of Berlin, which is an independent chartered corporation presently engaged in working out its relations to the State (*Land*), the technical universities are responsible to the Ministry of Education in the State in which they are situated. As a result, their constitutions are various, but the following remarks are typical of their structure.

The executive head of the university is the rector, who is elected from among the full professors (*Ordinarien*) of the university for a period of one or two years, after which he is normally pro-rector for a further one or two years. He is assisted by a permanent secretariat headed by a registrary.

The senate is the governing body of the university in so far as it is not overruled by the Ministry of Education, which has the right to control the university in great detail; the degree of friction between the two appears to vary enormously. In addition to the rector and pro-rector, the senate normally consists of the dean (*Dekan*) of each of the faculties (*Fakultät*) and a number of other professors elected by the faculties or special classes of teaching staff. The dean of a faculty is normally elected for one year.

The number and arrangement of the faculties varies from one university to another. Typical arrangements are outlined below.

Aachen.

I *Faculty of General Science.*

(*a*) Department of Mathematics and Physics.
(*b*) Department of Chemistry.
(*c*) Department of Economics and Cultural Subjects.

Mr. Welbourn is Dean of Selwyn College, Cambridge, and University Lecturer in Engineering.
Dr. Spalding is Professor of Heat Transfer, Imperial College of Science and Technology, University of London.
Mr. Ashdown is Senior Lecturer, Battersea College of Technology, London.

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II *Faculty of Civil Engineering.*
- (*a*) Department of Architecture.
- (*b*) Department of Civil Engineering.

III *Faculty of Mechanical and Electrical Engineering.*
- (*a*) Department of Mechanical Engineering.
- (*b*) Department of Electrical Engineering.

IV *Faculty of Mining, Metallurgy and the Production of Metals.*
- (*a*) Department of Mining.
- (*b*) Department of Metallurgy and the Production of Metals.

Within each department there are further subdivisions. Thus the Department of Mechanical Engineering has at present 13 active full professors (and 3 unfilled chairs), and each of these is head and director of his own institute. The institutes are: Machine Tools, Mechanics of Machines, Heat and Combustion Engines, Materials, Turbo-machinery, Aerodynamics, Transport, Textile Engineering, Aeronautics, Process Engineering, Control Engineering, Agricultural Machinery, Mechanics; one further institute, that for Inland Shipping, is situated at Duisburg and is only loosely associated with the university. An Institute for Work Study is directed by a reader (*ausserordentlicher Professor*).

In the Department of Electrical Engineering there are similarly institutes for Theoretical Electricity, Heavy-Current Electricity, Communication Engineering, High-Frequency Engineering, Electrical Plant and Sources of Power, Electrical Materials; and an institute for Theoretical Physics jointly with the Department of Mathematics and Physics.

Munich.

At Munich there is no faculty of mining, but instead there are faculties of agriculture and brewing, reflecting differing regional interests.

Berlin.

Berlin, with a somewhat different structure, teaches broadly the same range of subjects as Aachen, but in addition has agriculture and also one of the two schools of marine engineering in Germany.

The degrees awarded in all faculties give exemption from the First State Examination for the Civil Service; but the faculties of civil engineering are somewhat different from the others in that their degree serves as the professional qualification needed to meet statutory requirements for certain classes of civil engineers.

(2.3) The Structure of an Institute

Institutes are materially either separate buildings or self-contained sections of larger buildings. They have their own laboratories, workshops, libraries, secretariat, etc., and are run directly by the head of the institute.

Despite rules and regulations, the professor who is head of an institute has great freedom, not only to organize as he likes, but to teach and examine as he will; it is therefore difficult to generalize about institutes. Usually, however, the professor will be assisted by one or two senior demonstrators (*Oberingenieure*) who are paid by the university, and in addition a small number of assistants, paid variously, who work partly on research projects leading to a doctorate, and partly on teaching in the laboratory, drawing office and examples classes. The projects on which they are working are often ones which the professor is being paid for by an industrial organization; Germany lacks research organizations similar to those sponsored jointly by industry and the Department of Scientific and Industrial Research in this country, and as a result the institutes at the universities tend to fill the gap. Thus the Department of Mechanics of Machines at Munich is largely financed by the gearing industry; while the similar department in Berlin incorporates a special section for research on, and testing of, prostheses.

(2.4) University Teaching Officers and their Appointment

The structure of the teaching staff at a German technical university is extremely complicated. What follows is a simplified account of it.

A full professor (*ordentlicher Professor*) is a State official (except in Berlin, where the relations between the chartered body and the State are still being developed) who enjoys complete security of tenure to the retiring age of 68, when he retires on a State pension equal to his basic stipend. He is normally appointed on the advice of the faculty, supported by the senate. In strong contrast to the British system, a professor is called (*berufen*) to a chair and the post is never advertised. An occupant of a more technological chair will normally be someone who has been about 15 years in industry and has been 'called' at 40–50 years of age. It is unusual for a man to be occupying a full-time academic position when he is elected to a chair, since there is no academic ladder of established positions as in Great Britain. The concept of the professor as someone who has made his mark in industry, usually as a designer, is still widespread, although today more emphasis is laid on scientific attainments.

Professorial stipends vary widely, but would at present not be high enough to be attractive in comparison with those obtaining in industry were it not for the possibilities of doing consulting work and for the prestige attached to the title of Professor. Many chairs are at present unfilled. The initial stipend and the level of funds for his institute are matters for negotiation between the professor and the Ministry of Education on appointment; in addition the professor receives fees (*Colleggeld*) paid by those attending his lectures. The system was intended to reward the good teachers, but nowadays rewards professors in departments where study is compulsory for all students.

Readers (*ausserordentlicher Professor*) are similarly appointed to teach and to run institutes in specialized and new fields of study. In all respects they resemble full professors, except that they cannot be elected as rector.

Professors and readers occupy a very special position in the German system, since there is no class of teaching staff equivalent to our established lecturers. They carry the whole burden of lecturing on the fundamentals of their subjects; but for special topics they are often helped by industry, which freely lends members of its staff. The title of Honorary Professor is conferred on outstanding men who give regular courses of lectures.

Other external lectures (*Privatdozent* or, after six successful years of teaching and research as such, *ausserplanmässiger Professor*) are appointed by the university and paid from the students' fees. A suitable person may apply to the university for permission to give a course of lectures, and will usually be paid by results. Occasionally they are established as *Diätendozenten* with fixed stipends.

Yet other external lecturers (*Lehrbeauftragten*) are similarly appointed on a yearly basis.

Senior demonstrators (*Oberingenieure*) occupy permanent positions and are appointed by the university at the suggestion of the professor concerned. They are men who have had at least two years' experience as demonstrators and also two years of industrial experience who wish to return to the university for a period in order to do research work. They are essential in a large department to assist in the design office. It is assumed that they will return to industry.

(2.5) Professorial Assistants

Demonstrators (*Assistenten*), who are young men appointed to help a professor, carry a large part of the teaching load in the

laboratories, drawing offices and examples classes. They are appointed by the university for two years at a time, and normally for not longer than four years altogether. They usually spend about half their time assisting the professor, and are permitted to spend about half working for the degree of Doctor of Engineering (*Doktor-Ing.*). They are paid from institute funds, one or more being attached officially to a chair.

A small class of more senior demonstrators (*Oberassistenten*) comprises men who have obtained their doctorates and stayed on to teach and to do research without first getting practical experience outside the university.

Student demonstrators (*Hilfsassistenten*) are usually undergraduates in their last year who are paid hourly to assist in the examples classes, laboratories, and drawing office. The positions are much sought after, since they bring the men in direct contact with the professors, who are glad of the opportunity to guide a few of the ablest men of each year.

(2.6) Staff-to-Student Ratio

The ratio of professors to students is at present considered to be far too low, but if all grades of teaching staff are taken together, the ratio of staff to students appears to work out at almost 1 : 12, which is the figure in Great Britain. The ratio varies widely from one faculty to another, and mathematics departments tend to be worst off.

(2.7) The Undergraduate and his Schooling

Almost all undergraduates come to the universities directly from grammar schools at the age of 19½; a few have been at technical colleges (*Ingenieurschule*) first, where they have obtained a qualification similar to a Higher National Diploma. No equivalent of a London external degree exists in Germany.

School education varies from State to State, but normally all children attend the State schools, the primary school taking them from 6 to 10. Those going on to a grammar school choose one of three types, the classical grammar school (*Gymnasium*), the modern grammar school (*Realgymnasium*), or the science grammar school (*Oberrealschule*—other names are also used). Although nominally these are all of equal status, the classical schools enjoy a higher social standing, and many parents prefer them even for children intending to become engineers because they consider that the standard of teaching is better.

Despite the difference in names, the instruction at the three types of school has much in common, since admission to the university, whether ordinary or technical, depends only on passing the school-leaving examination (*Abitur*) successfully, usually at 18½–19½. To do this, all candidates must pass in four papers, taken at the same time, in German, mathematics, a foreign language, and either a second foreign language or a science subject. In our judgment (and for help on the languages side we are much indebted to colleagues used to examining in these subjects) the all-round standard represents in each subject what might be expected a year after 'O' level by those specializing in the English grammar schools.

We know the difficulty of forming a sound judgment on this subject, since not only do the standards of the various examining bodies in Britain vary in a notorious manner, of which those of us who select students for admission are only too well aware, but in Germany the standards vary from school to school, since the examining in many States is entirely internal, subject to general inspection by the State Ministry of Education.

We wish, however, to draw attention to a most important point. All boys and girls when they leave school have had to continue the study of mathematics up to the end, and have had to pass an examination in the elements of analytical geometry and of the calculus. In consequence about 20% of those who have done classics at school proceed to technical universities, where they form about 5% of all the undergraduates. They find the first year there difficult but not impossible, and are often preferred as pupils by their professors.

The classical and modern schools also teach some science, but there is a big variety in the amount.

Despite the fact that their own language is a compulsory subject in the school-leaving examination, we heard much dissatisfaction expressed concerning undergraduates' ability to use it—a familiar worry.

(2.8) Admission to the Universities

While the school-leaving certificate theoretically gives the right to attend any university and to read any subject, overcrowding has caused certain States to introduce numerical limits to admissions, and consequently to demand more than the minimum pass mark. However, enough places in engineering appear to exist in the country as a whole. We heard the view frequently expressed that numbers might profitably be reduced by at least 25%, and that the men concerned would do better by taking the equivalent of a Higher National Diploma course. Great concern is expressed at the lack of facilities for this form of course.

We deliberately do not discuss the scholarship position, which is in a state of flux.

(2.9) Pre-University Practical Experience

The school year in general ends in April, while the university year does not begin until November, so that six months are available in which to obtain the practical factory experience demanded of all undergraduates before they start on lectures, etc. A varied experience in the shops is demanded, but no high degree of personal skill is expected. On the other hand, carefully kept notebooks with sketches and drawings must be submitted to the university, together with a full report on what the student has seen and done. A further six months must be fitted in during subsequent vacations. Each student is examined orally on his experience and notebooks.

It should be emphasized that no undergraduate is allowed to start at the university until he can provide evidence that he has obtained workshop experience of the required standard, and the universities regard the conduct of this training as being far too important to leave in the hands of the firms. Moves are afoot in certain universities to reduce the workshop period from one year to a total of six months, by insisting that the firms carry out the training more efficiently.

The German Engineering Institutions, unlike ours, are not professional societies as we understand the term, and play no part in determining either the form or content of workshop training.

(2.10) General Outline of University Courses

In general, an able and very industrious man can obtain his degree (*Diplom-Ingenieur*) after 4 years' work, although at Munich he requires 4½ years and at Berlin, where the equivalent of a year must be spent on general education, 5 years. However, this is very seldom achieved for a variety of reasons, in particular the overloading of the courses. A number of those who know our universities attributed part of the trouble to the exaggerated respect paid to 'academic freedom' (*akademische Freiheit*) by which the undergraduate is left entirely to his own devices without any tutorial guidance, and as a result often wastes a lot of time in his first year or two.

The German academic year has two terms (*Semester*) each of about 14 weeks, although the first has a short break at Christmas. Except at Munich, where a deliberate effort has been made to reduce the hours of formal teaching, the laboratory work and lectures cover 5½ days a week; in Munich, only 5. Table 1 shows

Table 1

Semester	No. of Students
1	294
2	14
3	244
4	28
5	230
6	39
7	170
8	36
9 and higher	344
	1 399

by semesters the actual distribution of undergraduates at Karlsruhe reading mechanical engineering as at the 1st December, 1957, and offers a sharp comment on the nominal 4 years to graduation. The figures for other engineering faculties are similar.

The first examination may be completed after a minimum of two years, but more usually after 2½ years. At this preliminary examination (*Vorexamen*), which may be taken repeatedly, about 20% of all who start fail and leave the university. Of those who pass, probably only 2% fail to graduate. This latter figure is difficult to ascertain, since a certain amount of movement takes place from one university to another after the preliminary examination, and at present Berlin is gaining as many due to this movement as it loses.

While the work for the preliminary examination has been on a broad theoretical and practical basis, the work afterwards is heavily specialized in one direction or another, usually with a strong design bias. The final examination is on the diploma thesis (*Diplomarbeit*), which may at most universities be submitted at the end of 4 years, but is more usually submitted after 5 years.

Each undergraduate keeps an official book (*Studienbuch*) in which are entered particulars of the courses which he has paid to attend. We were given photostats of typical ones and saw others. Table 2 is an analysis of an official book of a Berlin student who

Table 2

NOMINAL PERIODS PER WEEK

Term	Engineering lectures	Arts lectures	Examples classes	Drawing office	Laboratory	Total
1	8	19	2	2	–	31
2	18	10	2	–	–	30
3	17	1	5	2	4	29
4	11	3	4	2	6	26
5	21	5	7	6	–	39
6	14	1	6	6	8	35
7	23	–	6	–	5	34
8	19	–	12	–	5	36
9	6	–	–	–	4	10*
10	6	2	–	4	–	12*
11	4	–	–	–	–	4*

A total of 30 weeks were spent in workshops during vacations.

* Not to be taken at face value, since projects are not included.

took his degree in 5½ years, i.e. half a year more than the minimum. He took his preliminary examination after 2½ years, the minimum time at Berlin.

We were informed that a lecture period nominally lasts 45 minutes, but that an examples class period implies at least two hours' work, and a drawing office period four hours' work. Laboratory time probably represents twice the figure given for hours of work. In short, it was freely admitted in Berlin and Aachen that the undergraduate probably needed to work 55 hours a week in term time merely to keep up. In Munich, a real effort has been made to bring this figure down to 45 hours a week, and Karlsruhe is trying to reduce it still further.

The figures in Table 2 for the last three terms are deceptively low, since they do not reveal work such as the diploma thesis, which represents three months of continuous work. Indeed, one professor said bluntly that during this period he expects his men to spend at least 10 hours a day, 6 days a week, at the drawing board.

(2.11) The Preliminary Examination (*Vorprüfung*)

No examination has to be taken or passed before the end of the second year, since it is felt that some relief from examinations is needed after the strain of the school-leaving examination.

Very few university examinations follow the British pattern, and the written examination paper (*Klausur*) was almost unknown until increased numbers of students made the traditional method of oral examination by the professor almost impossible in many institutes. We noted that books may normally be taken into written examinations, but that good men do not usually bother to do so. Examinations are generally a mixture of marked class work, both examples as well as laboratory and drawing office, written examinations, and oral examinations. A man who fails in a written examination may demand an oral; equally the professor may demand one.

Typical lecture lists[3,4] for the preliminary examination are those for Aachen given in Appendix 6.1.1, Tables 3 and 4. They are fairly similar both for electrical and mechanical engineers, and an undergraduate can change his department—although with difficulty—after the preliminary examination.

The method by which an undergraduate passes the preliminary examination (Appendix 6.1.1, Table 5) varies radically from one university to another; all expect course work to be shown up, but some use written examinations extensively, others depend on oral examinations, and yet others on a mixture of both. Nevertheless, all the universities accept men who have passed the preliminary examination at any of the other universities, and since the main object of our visit was to try to compare academic standards in the two countries, we have felt impelled to base our judgment more heavily on written examinations, which are relatively easy to assess, than on the course work.

The course work includes an amount of time in the physics laboratory which is normal by English standards, but we saw very little other laboratory work of the type usual in Britain, which consists in verifying elementary theory on simple apparatus or on machinery. On the other hand, the teaching in the elements of mechanical design applied to components of machinery such as gears, clutches, etc., was of a much higher standard than is usual here.

(2.12) The Diploma (or First Degree) Examination: The Syllabus

At Aachen, the diploma can be taken after a minimum of 4 years' work, but this is rarely done; indeed to do so often means a deliberate choice of 'soft options', sometimes for financial reasons.

The regulations for the examination vary from one university to another, but those of Aachen may again be taken as typical, and are quoted below extensively.

After completing the preliminary examination, the undergraduate has a choice of seven main lines of study in mechanical engineering and three in electrical engineering.

In mechanical engineering these are:

Prime Movers and Process Machinery.
Thermodynamics and Heat Engines.
Manufacturing Technology.
Transport Engineering.
Railway Engineering.
Process Engineering
Textile Engineering.

and in electrical engineering:

General Electrical Engineering.
Heavy-Current Engineering.
Communication Engineering.

We were informed by an industrial firm that the general electrical engineering course had been introduced only as a result of heavy pressure by themselves, as they were worried by the over-specialization of the young men joining the industry.

In order to pass the diploma examination, undergraduates must qualify in a number of different ways. In the first place, they must attend compulsory lectures and complete the course work attached to them with an adequate mark. Table 6 (Appendix 6.1.2) shows these for thermodynamics and heat engines. Secondly, they must attend lectures and do course work in additional subjects (Table 7) equivalent to at least 3 nominal hours per week. Thirdly, they must do 5 projects (*Studienarbeit*), 2 of which require 6 nominal hours per week for 1 term, and 3 of which require 3 nominal hours per week for 1 term. Two 3-hour projects may be combined to make a single 6-hour project. At least one of these projects must be a design, while the others may be design, laboratory, theoretical or scientific-literary projects. Fourthly, they must write a diploma thesis (*Diplomarbeit*), which is expected to represent 3 months' continuous work, and may be a design, a piece of experimental research, or more rarely a purely theoretical investigation.

The precise way in which these four classes of work are specified, and the relative weights given to them, varies from faculty to faculty and university to university. Thus in one case we were told that the three projects had to cover design, laboratory and theoretical work respectively, whereas in another we were told that it is common for the diploma thesis to be based on work done on apparatus which has been built and calibrated as a project. The diploma thesis is intended to be a piece of independent engineering work, such as a junior professional engineer might be expected to tackle in a firm, and for this reason the time allowed for it is usually deliberately limited, to emphasize the difference between the engineer, who must achieve results against the clock, and the scientist.

In addition, they must have completed a total of 12 months in approved workshops.

Tables 8–13 (Appendix 6.1.3) provide similar information with regard to the three electrical engineering courses, together with the examination plan.

(2.13) Post-Graduate Work

Our terms of reference related primarily to first-degree standards, but we also obtained some insight into post-graduate work.

Industry places much more value on a doctor's degree in Germany than it does in Britain, especially on the manufacturing side, where it is quite usual to find works managers who are doctors of engineering. This undoubtedly contributes to the ease of exchange of ideas between design, manufacture and research.

Generally a graduate stays on to do research at the suggestion of the professor under whom he has done his diploma thesis. If he is paid from the funds of the institute provided by the State he often spends about half his time on teaching as a junior demonstrator (*Assistent*). Alternatively, he may be researching full-time, paid by the institute from funds provided by industry. There are no time limits, but a thesis, on which he is examined orally, is generally submitted after about 3 years' work, the range being usually 2–4 years. The degree awarded is Doktor-Ing. and is roughly equivalent to a Ph.D. in Britain, although in technological subjects the analytical and theoretical content appears to us to be less than is demanded here.

One year post-graduate courses such as are becoming common here are unknown in Germany.

The equivalent of an Sc.D. is unknown in Germany.

(3) COMPARISON, COMMENTS AND CONCLUSIONS

The following opinions were reached by the team after analysis and consideration of the information obtained. While often expressed dogmatically, they are put forward tentatively, with the warning that we had too little time to probe very deeply and have had to rely on impressions rather than prolonged study.

(3.1) General Comparisons

Reliable comparisons with the British Dip.Tech. will be possible only when those with this qualification have spent several years in industry. In this Section we have concentrated on the British graduate engineer. Some comments relating to the Dipl.Tech. will be found in Section 6.2.

The standard of the Dipl.-Ing. is not strictly comparable with that of the British honours B.Sc. or B.A., since the two systems aim at different end-products. The British degree is firmly integrated into a course consisting of three years at the university followed by two years' practical training in industry (or into a 1–3–1 sandwich scheme) which broadly aims at satisfying the requirements of the professional institutions for corporate membership. In Germany, entrance to the technical institutions such as the Verein Deutscher Ingenieure and the Verband Deutscher Elektrotechniker is only dependent on having passed the final examination from a technical university or technical college. When, therefore, an attempt is made to compare the graduates of the two systems, the vital time is 5 years after leaving school, when the average man in England will be 23½ and will have completed both university and also a graduate apprenticeship; and the average man in Germany will be 24½ and will have completed one year in works and obtained his diploma.

Whereas British universities tend to teach engineering by placing major emphasis on analysis, German technical universities lay their major emphasis on synthesis, or design. The learning of facts is regarded as being more important in the German educational system than it is in the British, and tends to what we regard as overloading of the German syllabuses. It seems possible that our methods are better suited to the ablest men, theirs to the average and weaker men.

(3.2) Comparison of Standards attained by British and German Engineering Students

(3.2.1) **At School-leaving** (see Section 2.7).

German schoolboys specialize less than their British contemporaries. Thus even those who attend the classical grammar schools continue to study mathematics and science to a sufficiently advanced level to permit them to enter the technical universities and indeed to have very successful careers there.

We regard this feature of the German system as very satisfactory, because (i) it permits boys to decide the main line of their careers at a more mature age than in Britain, (ii) it avoids the loss to the scientific stream of bright boys channelled into the classical stream by enthusiastic schoolmasters, and (iii) it ensures that all boys, both on the arts and on the science side, possess a better general education.

The corresponding disadvantage is the lengthening of the university course by about six months. The German undergraduate spends much of his first year gaining scientific knowledge which the British boy has already learnt at school. This delays his attainment of professional effectiveness and economic independence. We do not consider that this is inevitable, since school curricula are considered by many educationists to be over-

loaded, and pruning of other subjects might allow of higher standards in the compulsory leaving-examination subjects.

(3.2.2) **At Entry to the Technical University** (see Section 2.9).

Also advantageous, in our view, is the German requirement that all students must obtain practical experience in workshops before entering the technical university. Although we gained the impression that it is difficult to ensure that the training they receive there is of a high standard, we feel that early contact with the engineering industry is bound to help the student to understand the significance of his later learning. We think that the six months on which they insist is a better period than the one year of our 'thick sandwich'.

(3.2.3) **At the Preliminary Examination (*Vorprüfung*) Stage** (see Section 2.11).

We believe that the German student at this stage has had about the same amount of knowledge made available to him as has the British student at the end of his second year at the university. It appeared to us, however, that (i) this knowledge tends to be imparted piecemeal and not as an integrated whole, and (ii) the student is never subjected to such a searching or concentrated test of his grasp of that knowledge as is afforded by the British examination system. The German student will be much more skilful at elementary design on the drawing board: the British will have more experience of running machinery.

(3.2.4) **At Graduation** (see Section 2.12).

In his final years, the German student acquires more detailed knowledge of a particular branch of engineering than the British, and does more independent work (*Diplomarbeit*). He generally also acquires considerable knowledge of drawing office and design procedures which universities in Britain scarcely attempt to impart. We believe he is certainly more fitted to begin a professional career than his British contemporary, if only because the world he enters is less strange to him.

We do not regard the tests which the German student undergoes as very rigorous, at any rate to obtain a bare pass, and find proof of this in the fact that it is rare for a student admitted to the final examination (*Hauptprüfung*) not to obtain his diploma.

(3.2.5) **At Professional Qualification.**

The German student has the standing of a professional engineer as soon as he obtains his diploma; he is therefore properly comparable with the British student who has just completed, at about the same age, two years' apprenticeship after graduation.

Without a careful survey of the British apprenticeship system, including the worse as well as the better schemes, we do not feel able, at this stage, to compare the products of the British and German systems with any certainty. However, we are strongly inclined to believe that, when operated well, the British system is at least as good as the German.

(3.2.6) **Summarizing Remarks about Knowledge obtained by Students.**

Theoretical.—The British system attaches somewhat higher importance to theory than the German, and presents it in a more unified and comprehensive form. There appear to be moves afoot in German technical universities to emulate us in this respect.

Practical knowledge.—The British student obtains more experience of operating and testing machines in the laboratory than does the German. He learns considerably less, however, during his university period of the processes and practice of engineering design and production.

The two are likely to be equal as far as workshop practice is concerned, but the man in this country is likely to have a much wider knowledge of the firm as a whole through having been moved systematically through all its main departments. We are of the opinion that far more graduate engineers are engaged in production in German industry than in British, to the great gain of German industry.

Design practice.—The British system gives relatively little attention to design. Although this is partly made good in the graduate apprenticeship, it seems possible that this lack of attention tends to lead to many British graduate engineers being inadequately experienced in the problems of mechanical design and tending to believe that design is a lower grade of activity than research—a wrong judgment in our opinion. Certainly British industry currently complains of a shortage of designers; but so does German industry.

(3.2.7) **Chemical Engineering.**

Although outside our terms of reference, we noted that chemical engineering has not yet established itself in Germany as a separate branch, but is usually taught piecemeal within the mechanical engineering and chemical faculties. We feel that German industry probably suffers in this respect. The matter is being earnestly debated in Germany.

(3.3) Organization of the German Technical Universities

(3.3.1) **Constitution of Teaching Staff** (see Sections 2.4 and 2.5).

In view of the radical differences between the German and British systems, we feel that some comments may be of interest. The big gulf between professors and other staff and the method of filling chairs appear to have the following consequences:

(i) The professors as a rule have wide industrial experience and so, in principle, are able to give students the knowledge and background which industry requires.

(ii) However, the professors often have, when they arrive, comparatively little knowledge of teaching, except at a very junior level.

(iii) The professors in many cases have extremely heavy teaching loads (often 13 and even up to 20 hours per week). They can therefore make little personal contact with their students, and their research also suffers. A student may never speak to a professor, except in the oral examinations, until he does his diploma thesis.

(iv) It is not possible, in the engineering faculties, to pursue an academic career of reasonable security except as a professor. While this avoids having on the teaching staff men who have forgotten that engineering teaching has an industrial aim in view and that the subject is a living one, it also has the disadvantages mentioned above. There is, of course, still nothing to prevent a professor from mentally fossilizing.

(3.3.2) **The Institute System** (see Section 2.3).

As stressed in Section 2, the institute is the professor's kingdom, in which he reigns supreme. This has the following consequences:

(i) An energetic professor can obtain an extremely lavish provision of equipment, particularly if he can arrange for his institute to serve as the research centre for an industry. Some institutes have something of the character of the industrial research associations in Britain. The equipment is such, in many cases, as to excite envy among British academic research workers, at least so long as they forget the associated administration. The system can lead to a diversion of effort into projects which according to British ideas belong more properly in an industrial research laboratory.

(ii) The activities of a professor and his institute are largely tied to a particular class of engineering equipment—e.g. steam engines Diesel engines, heating and ventilating—and not to a branch of applied science. The teaching is arranged accordingly.

As a result, the student will, for example, be taught thermodynamics anew at each institute, and each time in a different fashion This overlapping is wasteful of the student's time and is confusing Moreover, it tends to obscure the fundamental ideas. Although this disadvantage is recognized, many professors appear to regard efforts at unification and co-operation as infringements of their sovereignty. We understand that this problem has been tackled energetically and successfully at Darmstadt.

(iii) This inflexibility of organization, which can cause poor deployment of resources in a period when various technologies are changing in relative importance, also leads to extremely unequal loading: one institute may have a thousand students enrolled while another has only five. Again this disadvantage is recognized i

the German technical universities, but no way of overcoming it seems to have been found.

(iv) It must be admitted that the freedom of action accorded to a professor within his institute is one of the attractions which bring successful engineers back to the technical university. The insecurity of the lower teaching grades mentioned above gives the professor an enviable power to hire and fire, and to get his wishes carried out. We believe, however, that the absence of criticism from below can be unhealthy.

(3.4) Summarizing Conclusions

We are certainly not inclined to believe that the German engineering educational system is superior to the British when the graduate apprenticeship of the latter is taken into account.

Industry is not necessarily the best judge of whether a university is educating men for it in the best way, since one of the functions of a university is to pioneer new ideas. Nevertheless, its views must carry weight, and we therefore made some inquiries both in the technical universities and also in industry as to industry's views. The results were most illuminating. On the whole, the mechanical engineering firms appear to be satisfied with what the technical universities are doing, whereas the electrical engineering firms are dissatisfied, and complain that too much attention is paid to current practice and specialization in narrow fields, whereas they need more men well grounded in fundamentals in a very wide field. This attitude may be compared with that of British firms to the very broad education given by certain English universities in what amounts to classical mathematical physics applied to engineering. Here it is the electrical industry which approves, whereas the mechanical engineering industry tends to be critical that design is not taught and that little is said about workshop practice.

We think that the one respect in which the German system should be emulated is in raising the *status* of design in British universities. This does not mean, however, that we think as much *time* should be devoted to it as in Germany.

We should not be doing justice to our German colleagues, who discussed their problems freely and frankly with us, if we did not report that many of them consider that too much emphasis is laid on design in the technical universities. Almost everywhere moves are being made to re-emphasize the fundamental mathematical physics.

The ability of classically educated schoolboys to enter the technical universities is admirable.

We do not think that the organization and constitution of the German academic system should be copied, despite some enviable features—we wish we had in our universities, some of the equipment we saw. In any case, many German colleagues would like to bring their system into line with ours.

Rapid progress in engineering depends on a relatively small number of original minds and a rather larger, but still small, number of men of high ability and training. Owing to lack of the right to exclude men who have passed the school leaving certificate, the German technical universities find themselves clogged with men who should not be there, and unable to concentrate on the job of educating the best. Too many men who have been through the technical universities do jobs for which a technical college would have fitted them equally well. The same is true in Britain; but in post-graduate courses we have started to tackle the problem of educating the best in a way unknown in Germany.

All our generalizations can probably be confounded by numerous exceptions. They should not be accepted as the basis for action unless supported by more facts than we could gather in the time available. In particular, we feel that our criticisms of the German academic organization would meet outspoken disagreement in Germany, perhaps justifiably. We should like to hear it.

(4) ACKNOWLEDGMENTS

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(6) APPENDICES

(6.1) Data on Courses of Study

(6.1.1) **Preliminary Examination** (see Section 2.11).

Table 3

TYPICAL LECTURE LIST AT AACHEN—I

Term	1		2		3		4	
Subject	L	P	L	P	L	P	L	P
Higher Mathematics I–III ..	5	2	4	2	3	2	–	–
Mechanics (see Note 3)	3	2	3	2	3	2	2	2
Experimental Physics	4	–	4	–	–	–	–	–
Practical Physics	–	2	–	2	–	–	–	–
Projective Geometry	2	2	–	–	–	–	–	–
Materials I–IV	2	2	2	–	2	1	3	–
Principles of Chemistry	2	–	–	–	–	–	–	–
Machine Drawing I and II ..	1	2	–	4	–	–	–	–
Machinery Components I and II..	–	–	3	–	3	3	–	3
Kinematics of Machines (*Getriebelehre*) (see Note 4)	–	–	–	–	–	–	2	1
Principles of Electricity	–	–	–	–	3	2	–	–
Electrical Laboratory	–	–	–	–	–	–	–	3
Thermodynamics I and II ..	–	–	–	–	2	1	2	2
Experimental Measurement ..	–	–	–	–	–	–	1	3
Chip-forming Processes (*Zerpanungstechnik*)	–	–	1	–	–	–	–	–
Economics	–	–	–	–	2	–	2	–
	19	12	17	10	18	11	12	14
Total periods	31		27		29		26	

Note 1: L = 1 period lecture per week.
P = 1 period examples class, laboratory or drawing office per week, which should probably be multiplied by 2, 2 and 4 respectively to give hours.

Note 2: 'In addition, an active part should be taken in attending other lectures (*Studium generale*) of the student's own choice in order to deepen his general education.'

Note 3: Mechanics includes strength of materials, elementary structures and hydraulics.

Note 4: The scope of this is similar to Rosenauer and Willis: 'Kinematics of Mechanisms'.

Table 4

TYPICAL LECTURE LIST AT AACHEN—II

Term	1		2		3		4	
Subject	L	P	L	P	L	P	L	P
*Higher Mathematics I–III ..	4	2	4	2	4	2	–	–
*Mechanics I and II	4	2	4	2	–	–	–	–
*Experimental Physics	4	–	4	–	–	–	–	–
Practical Physics	–	2	–	2	–	–	–	–
*Projective Geometry	2	2	–	–	–	–	–	–
*Materials II–IV	–	–	2	–	2	–	2	–
*Principles of Chemistry I and II ..	–	–	–	–	2	–	1	–
Machine Drawing I	1	3	–	–	–	–	–	–
*Machinery Components I and II..	–	–	–	–	3	–	3	–
Principles of Electricity I and II ..	–	–	–	–	4	2	4	4
Electrical Laboratory	–	–	–	–	–	–	–	6
*Thermodynamics I	–	–	–	–	–	–	2	1
Alternating Current Calculations	–	–	–	–	–	–	2	–
*Economics I and II	2	–	2	–	–	–	–	–
	17	11	16	6	15	4	14	11
Total periods for compulsory subjects	28		22		19		25	

In addition, undergraduates are recommended to attend the following subjects to deepen their knowledge.

Atomic Physics I and II	–	–	–	–	2	–	2	–
Atomic Physics Examples ..	–	–	–	–	–	2	–	2
Mathematics Examples	–	–	–	–	–	–	2	2
Machine Components	–	–	–	–	–	3	–	3
Higher Mathematics IV	–	–	–	–	–	–	4	2
Total periods for voluntary subjects	–	–	–	–	2	5	8	9

* See Table 5.

Table 5

SCHEME FOR PRELIMINARY EXAMINATION FOR ELECTRICAL ENGINEERS

(i) Written or oral examinations in the subjects starred in the syllabus, Table 4.

(ii) Course Work in:
- (*a*) Physics Laboratory.
- (*b*) Electrical Engineering Laboratory.

(iii) Course Work in:
- (*a*) Higher Mathematics.
- (*b*) Projective Geometry.
- (*c*) Mechanics and Strength of Materials.
- (*d*) Machine Drawing.

(6.1.2) **Syllabuses for the Diploma Examination** (see Section 2.12).

Table 6

COMPULSORY LECTURES AND PRACTICAL WORK: HEAT AND PROCESS MACHINERY

Term	5		6		7		8	
Compulsory subjects	L	P	L	P	L	P	L	P
Fluid Mechanics I and II ..	2	1	2	1	–	–	–	–
Machine Tools I	2	–	–	–	–	–	–	–
Factory Organization	2	–	–	–	–	–	–	–
Manufacturing Processes ..	–	–	2	–	–	–	–	–
Materials V	2	–	–	–	–	–	–	–
Dynamics of Machines I and II ..	2	2	1	1	–	–	–	–
Components of Machinery ..	1	–	–	–	–	–	–	–
Reciprocating Steam Engines ..	–	–	1	–	–	–	–	–
Reciprocating Machinery ..	–	–	1	1	–	–	–	–
Internal-Combustion Engines:								
I. Theory	2	2	–	–	–	–	–	–
II. Design Fundamentals ..	1	1	–	–	–	–	–	–
III(*a*) Theory or (*b*) Design ..	–	–	1	1	–	–	–	–
Steam Turbines } Turbo-	2	–	–	–	–	–	–	–
Gas Turbines } machinery I	2	–	–	–	–	–	–	–
Turbo-compressors and Pumps }	–	–	2	–	–	–	–	–
Design of turbo machinery: Turbo-machinery II	–	–	2	2	–	–	–	–
Power and Heat Economics, including Steam Raising	–	–	2	1	–	–	–	–
Combustion and Furnaces I ..	1	1	–	–	–	–	–	–
Fundamentals of Heat Transmission I	–	–	–	–	2	1	–	–
Electrical Drives for Mechanical Engineers	–	–	–	–	2	–	–	–
Electrical Testing for Mechanical Engineers	–	–	–	–	–	4	–	–
Machine Laboratory	–	–	–	4	–	4	–	–
Combustion and Furnaces Laboratory	–	–	–	–	–	–	–	2
Fluid-Flow Laboratory	–	–	–	–	–	–	–	2
Total	19	7	14	11	4	9	–	4
Total periods per week	26		25		13		4	

Projects	5th to 8th term
Components of Machinery	2
Reciprocating Machinery	6
Turbo-Machinery	6
Free choice from voluntary or compulsory subjects	3
Free choice from voluntary or compulsory subjects	3
Total (equivalent to 5 periods per week) ..	20

In addition, attendance at a minimum of 3 hours per week in each term is required in the additional subjects, Table 7.

Diploma Thesis: whole of 8th or 9th term.

Table 7

ADDITIONAL LECTURES AND PRACTICAL WORK
(3 PERIODS MINIMUM)

Subjects from which to choose	5th–8th term L	5th–8th term P	
Special Topics in Turbo-Machinery	3	–	Group I
Boiler Design	2	–	
Heating, Ventilating and Air Conditioning	2	1	
Refrigeration Engineering	2	1	
Process Engineering (Thermodynamic fundamentals)	2	1	
Development Problems in Engine Design	2	1	
Rail Vehicles I and III	2	1	
Rail Vehicles II and IV	1	1	
Cranes and Conveyors I	2	1	
Cranes and Conveyors II	2	2	
Motor Vehicles I and II each	2	1	
Vehicle Engines I	3	–	
Machine Tools II	3	2	
Combustion and Furnaces II	1	2	
Measurement and Experimentation in Dynamics of Machinery	1	2	Group II
Welding Fundamentals	1	–	
Welding Practice I and II each	2	2	
Non-destructive Testing of Materials	2	1	
Electrical Measuring Methods I	2	–	
Special Topics in the Dynamics of Machinery	1	1	
Theory of Engineering Vibrations I and II each	2	1	
Mechanics of Similarity in Machine Design	4	–	
Higher Mathematics:			Group III
(*a*) Mathematics Examples Classes I–IV each	2	1	
(*b*) Theory of Functions I and II each	3	1	
(*c*) Differential Equations	3	1	
(*d*) Partial Differential Equations	3	1	
(*e*) Integral Equations	2	–	
(*f*) Conformal Transformation	3	1	
Higher Physics:			
(*a*) Lectures in Faculty of Physics (I)	2	1	
(*b*) X-rays and the Motion of Electrons	2	1	
(*c*) Physics of Materials	2	1	
Higher Fluid Mechanics:			
(*a*) Gas Dynamics	2	–	
(*b*) Flow Measurement	2	–	
(*c*) Gas Flow in Internal-Combustion Engines	2	–	
(*d*) Seminar	2	–	
Higher Mechanics	2	1	
Higher Kinematics of Linkages	3	3	
Higher Thermodynamics	1	1	
Special Topics in Thermodynamics	–	–	

At least one course must be taken from each group.

(6.1.3) **Recommended Timetable for the Final Examination in Electrical Engineering** (see Section 2.12).

Table 8

COMPULSORY SUBJECTS FOR ALL BRANCHES

Term	5		6		7		8	
Subject	L	P	L	P	L	P	L	P
Maxwell's Theory	2	1	2	1	–	–	–	–
Theory of Ions and Electrons	2	–	–	–	–	–	–	–
Principles of High-Voltage Engineering	–	–	2	–	–	–	–	–
High-Voltage and Discharge Laboratory	–	–	–	–	–	3	–	–
Principles of Electrical Machines	4	–	–	–	–	–	–	–
Design of Electrical Machines	–	–	–	4	–	–	–	–
Electrical Drives	–	–	2	–	–	–	–	–
Electrical Test I	–	4	–	–	–	–	–	–
Principles of Communication Engineering	2	–	–	–	–	–	–	–
Factory Organization	–	–	–	–	2	–	–	–
Manufacturing Processes	–	–	–	–	–	–	2	–
Instrument Manufacture	–	–	–	–	1	–	–	–
	10	5	6	5	3	3	2	–
Total periods for common subjects	15		11		6		2	

In addition, compulsory lectures, etc., must be attended according to Tables 9 and 10; a choice of additional lectures, etc., Table 11; projects according to Table 12; and a diploma thesis written.

Table 9

ADDITIONAL COMPULSORY LECTURES FOR GENERAL ELECTRICAL ENGINEERING

Term	5		6		7		8	
Compulsory Subjects	L	P	L	P	L	P	L	P
Principles of Electrical Measurement	2	–	–	–	–	–	–	–
Measurement Laboratory	–	–	–	–	–	3	–	–
Electrical Machines. II—Commutator Machines	–	–	2	–	–	–	–	–
Electrical Machines. III—Calculation of Machines	–	–	–	–	2	–	–	–
Electrical Machines. IV—Paralleling Problems	–	–	–	–	–	–	2	–
Electrical Equipment. I—Low-Voltage	–	–	2	–	–	–	–	–
Electrical Equipment. II—Medium-Voltage	–	–	–	–	2	–	–	–
Principles of Electrical Communication Engineering I and II	–	–	2	1	2	1	–	–
Telegraphy Equipment I and II	–	–	2	1	2	1	–	–
Telephony Equipment Laboratory I	–	–	–	–	–	3	–	–
High-Frequency Engineering I and II	3	1	3	1	–	–	–	–
Valves I and II	2	1	2	1	–	–	–	–
High-Frequency Laboratory	–	–	–	3	–	–	–	–
	7	2	13	7	8	8	2	–
Total of additional compulsory subjects	9		20		16		2	
Total of common compulsory subjects	10	5	6	5	3	3	2	–
	17	7	19	12	11	11	4	–
Total compulsory subjects for General Electrical Engineering	24		31		22		4	

Table 10.—Additional Compulsory Lectures for Heavy Electrical Engineering

Term	5		6		7		8	
Compulsory Subjects	L	P	L	P	L	P	L	P
Electrical Machinery. II—Commutator Machines	–	–	2	–	–	–	–	–
Electrical Machinery. III—Calculation	–	–	–	–	2	–	–	–
Electrical Machinery. IV—Paralleling Problems	–	–	–	–	–	–	2	–
Electrical Machinery Design ..	–	–	–	–	–	2	–	2
Electrical Test II–IV	–	–	–	4	–	4	–	4
Electrical Equipment. I—Low-Voltage	–	–	2	1	–	–	–	–
Electrical Equipment. II—Medium-Voltage	–	–	–	–	2	1	–	–
Electrical Equipment. III—High-Voltage	–	–	–	–	–	–	2	1
Steam Power Stations	–	–	–	–	2	1	–	–
Hydro-electric Power Stations ..	–	–	–	–	–	–	1	–
Principles of High-Frequency Engineering	2	–	–	–	–	–	–	–
Communication Engineering Laboratory I	–	–	–	3	–	–	–	–
Machinery Laboratory	–	–	–	3	–	2	–	–
Economics of Heat and Power ..	–	–	–	–	–	–	2	–
	2	–	4	11	6	10	7	7
Total of additional compulsory subjects	2		15		26		14	
Total of common compulsory subjects	10	5	6	5	3	3	2	–
	12	5	10	16	9	13	9	7
Total compulsory subjects for Heavy Electrical Engineering	17		26		22		16	

Table 11.—Additional Compulsory Subjects for Communication Engineering

Term	5		6		7		8	
Compulsory Subjects	L	P	L	P	L	P	L	P
Theoretical Fundamentals of Communication Engineering I and II	–	–	2	1	2	1	–	–
Communication Equipment I and II	–	–	2	1	2	1	–	–
Communication Laboratory I and II	–	–	–	–	–	3	–	4
High-Frequency Engineering I and II	3	1	3	1	–	–	–	–
Valves I and II	2	1	2	1	–	–	–	–
High-Frequency Laboratory I and II	–	–	–	3	–	4	–	–
Principles of Electrical Measurement	2	–	–	–	–	–	–	–
Measurement Laboratory ..	–	–	–	–	–	3	–	–
	7	2	9	7	4	12	–	4
Total of additional compulsory subjects	9		16		16		4	
Total of common compulsory subjects	10	5	6	5	3	3	2	–
	17	7	15	12	7	15	2	4
Total of compulsory subjects for Communication Engineering	24		27		22		6	

Table 12

Additional Subjects Chosen by Undergraduate

Group	General	Heavy	Communication
Minimum periods per week of chosen subjects	15	15	17
Of these, lecture periods ..	—	11	10
*Minimum number of subjects	—	3	2
Minimum number of periods per week in each subject	—	2	2

* These subjects must be taught by different persons.

Table 13

Examination for the Diploma in General Electrical Engineering

I. Written or oral examinations in:
1. Maxwell's theory.
2. Theory of ions, electrons and the principles of high-voltage engineering.
3. Principles of electrical measurement.
4. Electrical machines and drives.
5. Electrical equipment.
6. Electrical communication engineering.
7. High-frequency engineering, including valves.
8. Manufacturing engineering and economics.

II. Laboratory course work in:
1. High-voltage and discharge laboratory.
2. Measurement laboratory.
3. Electrical test.
4. Communication laboratory.
5. High-frequency laboratory.

III. Calculation and design of an electrical machine and transformer.

IV. Laboratory, calculation and design course work in the additional subjects chosen by the undergraduate.

V. Project in a field of electrical engineering.

VI. Diploma thesis in a field of electrical engineering or in another field by special permission of the department.

The examination syllabus for each of the other two options is similar in nature.

The examinations are not on the contents of the lecture courses, but on the fields concerned, and are intended to show whether men have done proper reading as well.

(6.2) Comparative Analysis of a Typical British and Typical German Course

A detailed analysis of a typical German and a typical British electrical engineering course was undertaken.* For the German course, Munich was chosen, for the sole reason that the information available was more complete. For the British course, the choice fell on the Diploma in Technology.

The London University B.Sc. course was considered, but the difficulties of comparison appeared too great, because the German student usually takes either heavy-current engineering or light-current engineering, whereas the British student of the B.Sc. course takes in his final examination both 'Power and Machines' and 'Telecommunication'. Although one of these is at main level and the other at subsidiary level, this only affects the marking scheme at the examination and not the course itself. Unfortunately we have inadequate information on any of the German general courses which might be considered as equivalent to the B.Sc., and to try to construct a course from the Munich

* Copies of the analysis can be obtained from the Secretary, The Institution of Electrical Engineers.

syllabus in accordance with the so-called 'free' section was considered to be worthless without a detailed timetable.

The Diploma in Technology as given at Battersea College of Technology is, on the other hand, divided more like the German course, and a comparison could be made for either the light- or heavy-current section. Here again it was the amount of information available which decided the choice of the light-current syllabus.

Those engaged in teaching for a particular diploma know only too well the shortcomings of the syllabus and the difficulties in interpreting it. Experience in teaching to a British syllabus and a knowledge of the subjects were used in combination in an attempt to analyse the German syllabus. Certain subjects, highly detailed in the British syllabus, appear in the German one under a more general heading. These were considered to be equivalent except where there was a large difference in the number of hours devoted to the subject. As far as possible the more general nature of the first two years of the German course was borne in mind, and the more detailed syllabus of the third and fourth years was used to assess the depth of the whole subject.

It is our opinion that a reliable assessment could be made only after attendance at selected lectures and practicals in order to determine the interpretation of the syllabus.

Taking the sections of the Battersea Diploma in Technology as a basis, the analysis led to following broad conclusions.

In *Principles of Electricity*, theory and measurements and engineering drawing there is little difference in the subject-matter. *Applied Heat* in the German course includes refrigeration, and *Electronics and Telecommunication* includes the techniques of high-vacuum production, neither of which is specifically mentioned in the Dip.Tech. syllabus.

In the *Engineering Physics* section, photo-electric and thermionic emission do not appear to be included in the Munich syllabus. On the other hand, there are in the German syllabus a number of items which a Dip.Tech. student would have covered before commencing his course. This accounts for some of the extra hours spent at the German University.

Strength of Materials and *Applied Mechanics* show little difference, but the German student spends more time on *Workshop Technology* and is given a greater insight into precision work. There is, however, no specific mention in the German syllabus of measurement techniques.

The time spent on *Power and Machines* is approximately the same in both cases, but whereas the German student is not concerned with power-system economics or with lighting, his course includes cross-field machines and magnetic amplifiers.

The main *Mathematics* section of the Dip.Tech. course includes elements of statistics, which appears to be absent from the Munich syllabus.

The two remaining sections of the Dip.Tech. course show considerable differences when compared with their German counterparts. This is to be expected, as in both cases these are specialized subjects. Many aspects of the *Measurements* section of the Dip.Tech. syllabus appear in earlier years in the German course. It is therefore impossible to establish a valid comparison in this section without more knowledge of the level at which these subjects are taught. In *Electronics* the German course includes radiation counters, X-ray tubes, particle accelerators and the electron microscope, whereas the Dip.Tech. syllabus specifies piezoelectric, magnetostrictive and ferroelectric phenomena, elements of automatic control, oscillators and the effect of noise in a system. There is thus a bias in the German course to more specialized techniques in electronics.

Comparison of hours spent on any particular subject can only be taken as a rough indication as, firstly, the German syllabus is in terms of periods which in some cases are less than one hour and in other cases are considerably more. Secondly, we have no means of taking into account the method of imparting the knowledge which may be by detailed lectures or by basic lectures supplemented by printed notes and/or private reading. The amount of detail, of a theoretical nature, in some of the laboratory notes issued to students would appear to favour the latter assumption. If this is so, the depth of teaching would, in the case of conscientious students, be greater than the German figures imply but probably correct for the less industrious.

[The discussion on the above paper will be found on page 424.]

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The Institution of Electrical Engineers
Report No. 2987
May 1959

PROBLEMS OF ENGINEERING EDUCATION

Report of a Group of German Professors who visited London, Rugby, and Cambridge, 29th June–9th July, 1958.

(*The report was read before a joint meeting of* The Institution of Electrical Engineers *and* The Institution of Mechanical Engineers *28th May*, 1959.)

THE MEMBERS OF THE GROUP

o.Professor Dr.-Ing. H.-G. Kayser (Brennstofftechnik), Technische Universität, Berlin.
o.Professor Dr.-Ing. K. Luerenbaum (Maschinenelemente), Technische Hochschule, Aachen.
o.Professor Dr.phil. Cl. Müller (Mathematik), Technische Hochschule, Aachen.
o.Professor Dr.phil. R. Sauer (Mathematik), Technische Hochschule, Munich.
apl.Professor Dr.rer.nat.habil. H. Stefaniak (Mechanik), Technische Hochschule, Munich.
o.Professor Dr.-Ing. R. Wille (Strömungslehre), Technische Universität, Berlin.

The group included three engineers, two mathematicians and one physicist.

(1) PURPOSE OF THE VISIT

In Great Britain the demand for more and better technologists and engineers has led to a remarkable expansion and development of the traditional university engineering faculties and moreover has given rise to new forms of higher engineering education at some of the leading technical colleges. In the discussion of these developments, reference has been made in Britain to the German technical universities and their courses leading to the degree of Dipl.-Ing. A team of English university teachers visited German technical universities in March, 1958, and our return visit was arranged in order to provide a wider background for mutual information.

(2) ACKNOWLEDGMENTS

The very kind invitation for our visit was conveyed by the British Embassy in Bonn. The Foreign Office and the Ministry of Education assumed responsibility for travel arrangements, accommodation and visits. Leading personalities of universities, colleges and industrial firms contributed to the success of our visit. Due to the excellent preparation of the programme and thanks to the readiness of our hosts to deal with our sustained flow of questions, it has been possible to take home with us a lasting impression of the well-founded and far-reaching plans for the development of engineering studies. To all the persons and organizations concerned we wish to express our thanks and our appreciation. We are specially indebted to Mr. D. B. Welbourn, Dean of Selwyn College, Cambridge, who with his excellent understanding of German university life was a most deeply-appreciated interpreter of the English academic scene.

(3) INTRODUCTION

The report is restricted to a tentative comparison of the English and German methods of organizing engineering education at university level. Problems of institutions without degree courses or their equivalent have not been studied.

The historical development of engineering studies in England has resulted in many kinds of higher engineering training which provide various roads to advancement. It is impossible to find parallels in all cases to German institutions and German nomenclature. We therefore are afraid that this report is not only incomplete but is in many respects weakened by somewhat crude comparisons.

Some of the more descriptive passages may appear superfluous to the English reader, but they had to be included for the benefit of the German reader, who needs more than a fortnight of travelling in England to grasp the meaning of 'Sandwich Courses' and 'Mechanical Sciences Tripos'.

(4) UNIVERSITIES AND COLLEGES OF ADVANCED TECHNOLOGY

We visited university engineering faculties at London and Cambridge. Of the colleges of advanced technology, we visited Battersea and Rugby.

English universities, unlike their German equivalents, are not responsible to the Ministry of Education. They are independent bodies and their right to confer academic degrees lies in a Royal Charter. Financial grants from the State are distributed by the University Grants Committee, a body to which no equivalent can be found in Germany, neither with regard to actual power nor with regard to its constitution.

The technical colleges, on the other hand, are responsible to the Ministry of Education, which provides and administers their budget. In this respect the technical colleges are similar to all German technical universities, except that of Berlin, which is a chartered corporation with its own financial administration.

We understood that within the Imperial College as a whole—which is a part of the University of London—it is the City and Guilds College which provides engineering courses comparable to those in our German faculties of mechanical, electrical and civil engineering. The statement that all undergraduate courses were honours degree courses did not at first convey anything to the German visitors, as all German technical university courses are at one and the same level.

In the Engineering Department of Cambridge University we saw courses of study for which no German parallel can be found; e.g. the fact that a student can take his B.A. degree in any of three courses, the standards of which are different. The best students, some 30% to 40%, take the first part of their final examination—Part I, Mechanical Sciences Tripos—as early as the end of their second year. During their third year some specialization takes place leading to Part II. The greater part of the students takes Part I at the end of the third year. This examination is a very general one. An undergraduate studies engineering in general and not mechanical or electrical or aeronautical engineering. Specialization of this kind is provided only for those reading for Part II in their third year. For the teacher this system means that the subjects of Part I have to be taught at two different levels.

The Council of The Institution of Electrical Engineers wish to express their thanks to the authors for permission to publish the report.

Students lacking a first-class knowledge of mathematics can reach their degree by a course called 'Engineering Studies'. About 10% of all engineering students follow this path. The decision whether a student takes the three-year honours course to Tripos Part I, or the three-year course in engineering studies, is taken on the strength of an examination at the end of the first year.

Battersea College of Technology is one of the new Colleges of Advanced Technology. Students can choose between two courses, namely University of London Courses or Technological Diploma Courses.

Battersea is not a part of the University of London, it is true, but it is a 'Recognized Institution of the University of London' in the faculties of science, engineering and music. Many members of the teaching staff are 'Recognized University Teachers'. An engineering student at Battersea who follows the University of London course acquires the degree of B.Sc.(Eng.), but in contradistinction to Imperial College, the courses at Battersea are not honours degree courses.

The diploma courses at Battersea have their emphasis more on the practical side of engineering. The newly introduced Diploma in Technology (Engineering), Dip.Tech.(Eng.), is not an academic degree like our German Dipl.-Ing. The Dip.Tech.(Eng.) is awarded by the National Council of Technological Awards. The course is a combination of three to four years' work at the college, with at least one year in industry. This year in industry is not a parallel to our German pre-university practical experience, during which our future students are intended to gain some skill in and a practical knowledge of manufacturing processes. The year in industry, fitted into the Dip.Tech.(Eng.), course, demands more or less the proficiency of a trained engineer.

Rugby College of Engineering is in many ways similar to Battersea. Students may choose between a course leading to an academic degree or a course leading to the Dip.Tech.(Eng.). In Rugby, too, the academic degree is that of the University of London, but while at Battersea one acquires the London internal degree, at Rugby it is the London external degree.

A remarkable variant in higher engineering education, provided by the colleges of advanced technology are the sandwich courses. The term 'sandwich' indicates that the students alternate half-yearly between college and factory. This type of engineering education should be specially successful if, as in the case of Rugby, a well-staffed and well-equipped technical college is in the neighbourhood of two big and famous manufacturing companies.

Summarizing what precedes, we find that in England higher engineering training is based on two different concepts. The old engineering faculties of the universities concentrate on general and applied sciences. The colleges of advanced technology direct their courses towards the more practical sides of engineering. To employ German terminology, we are tempted to say that the engineering sciences (*Ingenieurwissenschaften*) are taught at the universities, whereas the art and craft of engineering (*Ingenieurkunst*) is emphasized at the colleges. In a modern community, it is true, engineers have a great variety of tasks, but a strict separation of science and art in engineering education does not appear desirable. However, we feel that the English development of two separate types of institution for higher engineering, one with emphasis on scientific principles, and the other with emphasis on technical principles, meets the requirements of our time. The fields of teaching and research have become too complicated and too extensive, and a student during his four or five years of training cannot devote equal attention to both sides of engineering.

(5) PROFESSIONAL INSTITUTIONS, INDUSTRY AND UNIVERSITY

In England the academic qualifications conferred by degree and professional qualification as an engineer are two separate and distinct things. In Germany the academic degree Dipl.-Ing. is at the same time a professional qualification. In England the universities provide the preparation for a career in engineering, whereas recognition as a full member of the profession lies with the institutions.

The institutions have been incorporated by Royal Charters, and they set their own qualification examinations.

The German system has two disadvantages: the term Dipl.-Ing. (*Diplom-Ingenieur*) has a dual meaning, and it is often employed to suggest, unfairly, a better-trained engineer; and the technical universities bear the twofold load of academic and professional training. We formed the impression that the English professional institutions have many advantages. They seem to be the proper place for ascertaining views on the adjustment of professional standards, and through their qualification examinations they set and maintain a recognized standard for the profession. Furthermore, the institutions exert some influence on the university examinations, since it lies in their discretion to accept certain university examinations as exempting from part or whole of the professional examinations.

In Germany it is often said that only the theoretical foundations of engineering are taught at English universities, roughly corresponding to the subjects of our first two years. This statement is incomplete. It is true that an English engineering student during his three years at the university has no opportunity to apply his knowledge of a machine by designing one, and in his lectures practical problems of industrial production are only occasionally treated. But it must be borne in mind that professional training does not end with the academic degree. A university graduate who joins an industrial firm has the status of an engineering apprentice; not until some four years have elapsed can he qualify for the membership of an institution.

During our visit to the works of the British Thomson-Houston Company we learned how a five-year scheme of engineering training operates. The most modern way is a five-year sandwich course at Rugby College of Technology. Another possibility is to take one year's basic training in the works, followed by three years at a university and another year of special training in various branches of a big company.

Our impression is that big firms in England devote much time and money to the further education of their young graduate members. Very much is done for very small numbers in order to raise the standard of a few outstanding people.

It is conceivable that the big industrial firms can build up their own training departments. But we could not get a clear picture of what smaller firms were doing with their university graduates. In the discussion we learned that, in England as in Germany, small and medium-size firms are becoming more and more interested in university graduates. In small firms, as, for example, in the field of air conditioning, the graduate of a German technical university usually fills a fully-paid post after a comparatively short time. The German courses provide a well-balanced combination of instruction in scientific principles and applied science in specific fields of engineering studies. If we have understood correctly, we feel that the new Diploma in Technology courses will be of great value to all industries in which additional training on a wide basis cannot be provided.

In England, as in Germany, the larger firms do not usually attach much importance to whether a recently graduated engineer can be employed immediately in a normal capacity. He is expected rather to bring with him a good comprehensive knowledge of mathematics, mechanics, metallurgy and thermo-

dynamics or electrical engineering, as deficiencies in these subjects cannot be remedied once his professional career has begun. It is expected that university trained engineers will be able to engage in fundamental research and to draw on knowledge in all fields of science. For such engineering tasks the graduate from the Imperial College or from Cambridge is better prepared than the German Dipl.-Ing. The English student throughout his undergraduate years lives in a purely academic atmosphere; it is not until the beginning of his apprenticeship in industry that he comes into contact with empirical methods and with such facts as can be acquired by application. Practical facts are learnt from those who are occupied directly with these problems.

We learnt that each of the four establishments we visited ran post-graduate courses. These are broadly planned courses for engineers who are already following their profession. They deal with special subjects such as 'Nuclear Energy' or 'Gas-Turbine Engineering'. They run for a full academic year and end with a final examination for which the successful candidates are awarded a special certificate.

These post-graduate courses make great demands on the teaching staff, since the latest developments in a given field are always treated. We gained the impression that they are equally valuable to university and industry. It is to be regretted that such courses are not to be found at German technical universities.

To summarize: it can be stated that the English plan, of dividing the higher education of engineering into a more strictly practical-cum-technical and a more strictly scientific type of study, meets the requirements of the various industries and the demands of firms of the most varied character.

It has already been remarked (Section 4) that the non-uniform organization of engineering studies in England corresponds also to the differing abilities of young students besides taking account of the necessary limitations in the length of university studies.

(6) TEACHING STAFF, TEACHING METHODS AND EXAMINATIONS

A university teacher is both teacher and scholar. This dual function distinguishes universities from institutions concerned with a purely vocational training. This is, of course, also true of Germany. In contrast to Germany, it is endeavoured in England to co-ordinate research projects within a department. The possibility also exists of varying an individual's load of research and teaching from year to year. This is a consequence of the hierarchical structure of an English university department.

The English concept of 'education and research', which corresponds to the German '*Lehre und Forschung*', applies to individuals as well as to institutions. 'Education' comprises more than '*Lehren*' (i.e. teaching) by lectures, examples, and seminars. English universities consider it their task to contribute to educating the student for life in society by providing halls of residence for teachers and students. Rows of streets are being converted into students' quarters in the neighbourhood of the generously planned new Imperial College. At Rugby, new houses with modern single rooms for students are being put up simultaneously with the new building for the laboratories in the grounds of the Engineering College. This expenditure, which is very considerable by German standards, is being undertaken also on behalf of the sandwich students. It is our impression that the halls of residence in England are an integral part of the university, just as much as lecture rooms, laboratories and libraries.

At Cambridge and Imperial College very good provision for research on the part of the teaching staff as well as the students has existed for a long time. This provision has been completely renewed in recent years. We saw teaching and research laboratories in the department of aeronautics at Imperial College which are superior to anything to be found in German technical universities.

The two colleges of advanced technology which we visited, at Battersea and Rugby, are experiencing a period of development with regard to their new responsibilities. At Rugby we saw old laboratories used by students of high-frequency engineering which in respect of the equipment and the nature of the problems dealt with are comparable with the corresponding German facilities. We noticed at Battersea that, in the reorganization of the engineering laboratories, small modern units, e.g. refrigerating plants, were preferred in order to facilitate a student's view of the gauges.

Besides the many new facilities, as a consolation for our own universities, there are still to be seen veterans whose bearing bushes will not need to be adjusted even by another twenty generations of students.

A notable difference between the German technical universities and the English establishments we visited consists in the formal structure of the teaching staff. Whereas the whole responsibility for teaching in Germany is in the hands of the professors, there is a difference in the official designations in England: Professor, Reader, Senior Lecturer, Lecturer. The various positions differ in remuneration and indicate possibilities of advancement within one and the same department, without, however, indicating academic qualification or the degree of responsibility for teaching and research. It is possibly correct that a leading personality cannot be attracted to the university without being offered the post and title of Professor, but it is quite certain that there are just as outstanding scholars among the readers and lecturers as among the professors. The official designation of Professor appears to be restricted at present to universities. At Battersea and Rugby, where the courses of studies lead to a university degree, no member of the teaching staff holds the title of Professor.

This digression should serve merely to indicate that the external form of the English establishments does not provide a means for assessing the level of studies and research.

One category of English university teacher with which we are unacquainted in Germany is the Head of the Department. At a German technical university the academic post of a *Vorsteher der Abteilung Maschinenbau* (i.e. Head of the Department of Machine Construction), or of Dean of the Faculty of Mechanical Engineering, is mainly an honorary appointment, the holder of which prepares and conducts the respective meetings as *primus inter pares*. A Head of Department, however, by virtue of his office and on the strength of his scholarly reputation can profoundly influence the form that teaching and research take in the department.

In a German department or faculty a large number of professors are at any given time in a position of equality, and it is very unusual for a single personality to be able to exercise a sustained influence on the teaching and research activities of the combined teaching staff. We are fond of saying that the German universities are republics of scholars, and imply thereby a favourable situation, at least as far as the professors are concerned.

An English university department shows the forms of a hierarchical structure and as a consequence affords the possibility of an even distribution of the teaching load and within certain limits of annual readjustment.

In Germany we are of the opinion that responsibility for the lectures, as the keystone of university teaching, rests with the professors. It is true that we entrust young assistants with the supervision of examples classes, without, however, relinquishing responsibility for this branch of teaching. In the lectures we,

so to speak, deploy a large force of knowledge and experience. In England the approach is different. In all or most lectures the students meet young lecturers who were themselves a short time previously still students, even though very able ones, and it is frequently the case that the gap between the teacher and the taught is quite narrow. As a matter of interest we should like to mention that we could not presume to apply a higher standard of examination questions in the final examination for the diploma (*Diplomhauptprüfung*) than is general in England.

In the Engineering Departments at Oxford and Cambridge, it is expected that most members of the teaching staff should be able to teach every subject in the 3-year undergraduate course. One of the reasons for this is that Oxford and Cambridge colleges expect their teachers to take part in supervision. The hierarchical structure of their teaching staff favours such versatility, because the material and syllabus are scrutinized and revised at regular intervals. Narrow limits are set in respect of the personal and individual form given to the lecture, but the whole syllabus is carefully planned and immediate in its content.

We are of the opinion that this procedure has many advantages with regard to the favourable employment of the time available for study, and also with regard to an even distribution of the teaching load. We see, however, a disadvantage in the fact that the syllabus, aiming at a fixed examination level, is pursued almost along school lines. The personality of the teacher and the individual characteristics of the methods of scholarship of a professor do not in most cases appear in the undergraduate courses. In our opinion these lecture courses should be supplemented by courses of lectures which are fully imbued with the teacher's approach and experience.

All examinations in engineering at the English universities are written ones, in which the name and the identity of the candidate are unknown to the examiner. The examination questions are set by a university committee which includes representatives from outside the university, in order 'to guarantee', as it runs in the statutes, 'an unvarying level of achievement'.

This procedure has the advantage that the standard can be controlled and readjusted at any time. The disadvantage of the procedure, it appears to us, lies in the fact that, because of the limited number of possible permutations which can be set, their repetition cannot be avoided. As a result, there is a danger that the student relies on old questions in preparing for the examination and that an understanding of scientific principles is replaced by a clever treatment of constantly recurring questions.

In the German system of oral examination the variation of the question is also limited. But an examiner is quick to realize from the answers given by a candidate whether the actual background of the problem has been understood, whether independent thought is being expressed or whether purely *ad hoc* ideas are being produced.

We were frequently asked how the standard in our oral examinations was maintained and guaranteed. This is a difficult question. It is not usual at technical universities in Germany for colleagues in a given department to exchange information concerning the character and scope of examination questions.

On the other hand, it is well known that different professors, even at different universities, will form almost exactly the same impression of a given student's capabilities. A standard seems to exist, consequently, even in the absence of any direct written or oral agreement, which all examiners recognize. Mutual agreement on this standard is achieved in part by means of the written examples which the student is required to complete and which are available to every member of the teaching staff.

Furthermore, the German system of supplementing the teaching staff determines the examination standard to a very considerable extent, and this standard is the same at all universities. The number of technical universities in Germany has never exceeded ten. A university teaching career without industrial experience is most unusual in the engineering faculties. The appointment to a professorship can be made in one of two ways: either directly from industry, or some ten or twenty years after the person concerned has taken his doctorate or his 'habilitation'. [Habilitation is the professional qualification entitling the holder to teach at a German university (*venia legendi*). In the case of a professorial appointment, neither doctorate nor habilitation is necessary.] It is also a rule, even though not without exception, that a first appointment to a professorship is not made at the university where the doctorate has been acquired or where the *venia legendi* has been awarded.

By the exchange of outstanding teachers within a small number of universities, the standard is maintained at a uniformly high level, and an absolute standard is represented in the scientific achievement of outstanding individuals.

At none of the four establishments which we visited were lecture classes large. Some lectures were attended by 100–150 students, but an attempt is being made to limit the number to 40–50. The number of students accepted by a given department is related to the number of teaching staff and the load they can be expected to carry. As a rule the ratio is of the order of 1 : 8 to 1 : 12, related to the whole institution and the total teaching staff.

Engineering studies at Cambridge are pursued on very general lines. The studies are engineering, not civil engineering, mechanical engineering, etc. All subjects in the engineering courses, including mathematics, are taught by members of the staff of the Engineering Department, and, in general, those teachers are preferred who have themselves pursued their studies in this Department. The professors and lecturers in mathematics are not associated in any way with engineering studies.

At a German technical university there is no organization comparable to such a department. The brief impression which we gained of this unique Cambridge institution does not permit us to venture a judgment.

(7) UNIVERSITY AND SCHOOL

At the end of secondary school education in Germany the *Reifezeugnis* is awarded. This is not only a certificate to the effect that the necessary standard has been reached for pursuing a course of studies at a university, but is also an entitlement to admission to a university. The English General Certificate of Education (G.C.E.) merely testifies that the prescribed standard has been reached. It is not an entitlement to admission to a university.

The English universities are able to make admission dependent upon success in an entrance examination, or they can demand evidence of high marks in individual subjects taken in the G.C.E. examination. As the G.C.E. examination is not simply a school-leaving certificate, but rather can be used to obtain admission to a particular university in order to pursue a definite course of studies, it follows that the English universities are able to exercise a considerable influence on determining the level of the G.C.E.

It is without question of great advantage in technical studies if a university is in a position to ensure that candidates shall have reached a high standard in mathematics and in the natural sciences whilst still at school. At the same time there is, in our opinion, a disadvantage that in England an excessive emphasis on individual subjects and an attendant narrow specialization can begin at school. A pupil planning to read engineering at Cambridge is able at, say, the age of 16, to specialize during his final school years up to the G.C.E. advanced level, in mathematics and natural sciences, so as to obtain the high marks

required in the subjects by Cambridge. In other subjects he can content himself with doing just enough to pass.

For historical reasons it has resulted that most potential engineers would like to study at Cambridge if possible. Consequently Cambridge has the first choice from a large number of excellent candidates and is therefore in a position to maintain a steady influence on the entrance standard. Imperial College is in a similar position, but it seemed to us that the two colleges of advanced technology we visited are not so fortunate. We consider it possible, however, that this picture will change as a consequence of the introduction of the new course of studies. Dip.Tech.(Eng.) courses will appeal to precisely those students for whom there previously existed no opportunity to study at university level, namely those who incline towards the practical side of the engineering profession.

(8) CONCLUSIONS

Whereas in Germany engineering training must be discussed in the context of the final diploma examination of the technical universities, in England it is the examinations of the universities and also those of the professional institutions which are of first concern.

English universities are able to concentrate on the training of future engineers with a firm grounding in basic scientific principles, and the emphasis in the university engineering faculties is placed on the mathematical and natural science disciplines.

In the engineering departments of the new colleges of advanced technology, engineering studies are directed more towards practical subjects—through either sandwich courses or courses in workshop practice, design and management. This dual approach to engineering studies at establishments of university standing is in our opinion a good one, in the light of the requirements of the modern industrial society and also in view of a necessary limitation of the time devoted to study.

Professional training is an integral part of courses of scientific studies at the German technical universities. This makes considerable demands both on teaching staff and students. German students of engineering have to spend five years (and more) at the university. It is the English view that it is wrong to keep a young man a student for longer than three years. University studies and professional qualification are consequently kept apart.

When one considers that large numbers of students in England are in receipt of grants, this system of dividing the period of training seems to be advantageous as regards the distribution of the financial burden.

All German technical universities have a uniform curriculum for the respective fields of engineering. (Such variations as do exist are of no importance within the context of this report.) This is necessary on account of the combination of professional training with the course of studies. The English universities are in a position to develop special characteristics and to impress upon their academic examinations a different accent and a different standard, because the professional qualifications of engineers in England are regulated by the professional institutions.

Since the English universities do not claim to provide a full engineering training, they are able to adapt themselves easily to the rapidly developing trends of modern science: it is not necessary to wait until an expert has been found in industry in order to be able to provide teaching in a new field, but instead one can simply entrust this field to a young university teacher who then develops it.

The teaching methods in the undergraduate courses appear by German standards somewhat elementary and too closely related to the examination. The student at a German technical university learns more about the whole scope of a field of knowledge, and the professors endeavour to give their students an intimate contact with theory and its application, and this in their own individual way and by reference to their own research. We have the impression that what we call *eine akademische Vorlesung* in Germany appears in England only at the stage of the post-graduate courses.

We believe that more could be done in Germany in the first and second years of study in the form of instruction (*Schulbetrieb*). The optimum probably lies somewhere between the English and the German methods.

We gained the impression that the importance of engineering studies to the life of the nation is appreciated to a far greater extent in England than in Germany. The colleges of advanced technology and the engineering faculties of the universities have new buildings, the planning and equipment of which clearly reveal that, not only are existing gaps being filled, but plans are being made on a broad scale for the future benefit of industry.

DISCUSSION ON THE ABOVE PAPER AND REPORT BEFORE A JOINT MEETING OF THE INSTITUTION OF ELECTRICAL ENGINEERS AND THE INSTITUTION OF MECHANICAL ENGINEERS, 28TH MAY, 1959

Mr. E. D. T. Jourdain (Lord President's Office): On behalf of the Lord President's Office, I should like to say how grateful we are to Mr. Welbourn and his colleagues and to Professor Wille and his colleagues for undertaking these studies.

As part of the Lord President's general concern for science and scientific policy, he is greatly concerned with the policy of providing adequate numbers of scientists and technologists. He takes a great interest in the developments which are now taking place in the field of engineering education, such as the colleges of advanced technology and the expansion of the universities, and it was felt that at such a time it would do nothing but good if we took advantage of what was already in operation abroad so that where necessary we could adopt the best practices of other countries. It was with this in mind that the Lord President's Office, with the aid of the Foreign Office, arranged for Mr. Welbourn to take a small party over to Germany in order to study and to report upon the educational systems in that country for mechanical and electrical engineers. Similarly, we were very glad to welcome Professor Wille to this country in order to give us an outsider's view of some of the problems which arise here.

We hope that this interchange will be regarded as of value by those who are responsible for the development of engineering education in this country, and we look forward to further exchanges in the future, both with other countries and between other types of engineers.

Dr. K. R. Sturley (B.B.C.): Five years ago I received an invitation from the Foreign Office to examine certain aspects of industrial training in Germany, and during that time I was able to visit the Ingenieurschule in Hamburg, the Technische Hochschule in Hanover and the Technische Universität and Ingenieurschule Gauss in Berlin. In looking over my report on this visit I find a number of my observations are paralleled in the present reports and some are worth underlining. The first concerned the professor, who in Germany is seen as a highly-qualified specialist with a title derived from a section of electrical engineering and not from electrical engineering as a whole. This has

some advantages since a specialist is often very enthusiastic and sometimes shows more drive than one who is concerned with a wide field of activity. There are two disadvantages: the specialist can be too obsessed with his own subject and there is therefore a tendency for technical efficiency to be regarded as more important than the true education of the student. In the Technische Universität in Berlin a department devoted to the humanities was responsible for 12–15% of an engineering student's time, but this 12–15% was regarded by some engineering professors as lost to their subject with little gain to the student; it would be interesting to know whether their attitude has changed. We in this country are very aware of this particular problem, and Prof. Mansell Jones in a letter to *The Times* (25th May, 1959) indicated our own dilemma.

Another observation concerned the mobility of the undergraduate, who is able if he so wishes to wander from one university to another. This has advantages but also disadvantages, the chief of which is that it discourages the professor from close contact and personal interest in his students. The mobility at undergraduate level contrasts markedly with the difficulties in changing from one educational stream to another, for example from an Ingenieurschule to a Technische Hochschule. Transfer across the educational ladders is much easier in this country.

It is perhaps not surprising to find that in Germany there are relatively few courses at post-graduate level. They are less necessary when a student has an additional two years of training, particularly when that training is biased towards design. The impression one gains of German electrical engineering education is that professors try to foresee and put before the student as many as possible of the kinds of situation which he is likely to meet in his industrial life. We take an entirely different view and feel that it is impossible to visualize what a man will have to face in the next 30 years, and only try to give guiding principles to help him deal with each obstacle as he meets it. There are objections to spending a longer time at the university with its rather cloistered atmosphere, and I recall an experience of earlier days when I was a training officer to an electronics firm. The graduates we recruited were given a specialized six months' training course before they were sent to the research or development department. When asked for their comments after the course many replied, 'We liked it but would have preferred to have it after about a year in the factory. We felt we wanted to earn our living and the six months' course seemed to be merely a continuation of our university studies'.

The German method of relying very largely on an oral examination at the end of the university course has considerable merit because it does enable a man's standard and depth of knowledge to be probed rather more fully than by a written examination, in which the choice of questions may be a lucky or unlucky one for the candidate. The chief disadvantage of the oral examination is that it is very time-consuming.

In discussing education it is very difficult to be objective and extremely easy to see where the other country fails. It is more profitable to examine those aspects where the other country appears to do better, and there are two ways in which we can learn something from the Germans. I think that for the majority of graduates the stress which is laid on design and production in German universities is very valuable. We in this country are inclined to place research on a pedestal and put it before the student as the be-all and end-all of his career. Research is undoubtedly a most important activity, but relatively few of those who graduate are fitted to undertake it. The longer period of time spent at the university by the German engineering student and the stress laid on design and production are of considerable help to the graduate who enters the small industrial firm. It seems likely that the number of graduates entering such companies will increase year by year, and unless they are able to gain the same experience as their colleagues in the large firm, their professional usefulness will be limited. This emphasizes the need for increasing attention to be paid to the group training scheme for graduate engineers in the smaller firms.

Dr. B. V. Bowden (Manchester College of Science and Technology): Engineering has been taught on the Continent in institutions of university rank very much longer than it has been in England. The Technische Hochschule in Charlottenberg began in 1799 and had achieved a position comparable to any other university in Germany before the middle of the last century, by which time many other similar Hochschulen had been founded in other European countries. In this country, on the other hand, the first large university school of engineering was not founded until about 1870. Our universities contributed little or nothing to the industrial revolution in England. Other countries developed their technological universities in the hope of industrializing themselves. The growth of the Continental Hochschulen since the war has been very rapid and most impressive; for example, during the last ten years the Germans have created in Aachen a Hochschule devoted entirely to the education of scientists and technologists which is as big as Oxford or Cambridge. Its size was determined partly by the belief that a properly equipped institute of technology should have about 100 professors. There are 127 professors and 9 000 students at Charlottenberg, so that the number of students per professor is about the same as it is in English universities.

The contacts between local industry and Hochschulen are very intimate and are fostered in several ways. In the first place eminent local industrialists are often elected to membership of the university staff as extraordinary professors; such appointments are particularly important in the development of new subjects hitherto unknown in the university world, such as for example the design of machine tools. The directors and senior staff of the Max Planck Institutes (which are research stations comparable in some way to our own D.S.I.R. stations) are almost invariably extraordinary professors or members of staffs of local universities.

Of the 28 countries listed by Unesco, all except Turkey and Norway have a greater proportion of their population at a university than we have. Almost all American children stay at school until they are 18 and go to a university or college afterwards. In this country 60% of our schoolchildren leave at 15 or 16, only 1 in 8 goes into the sixth form and 1 in 16 to a university. The figures which are shown in Table A cannot be explained away by arguments based solely on differences in standard between our universities and other people's and on the difference in functions of universities in this country and those abroad.

Table A

Country	No. of students in universities	Population	Approximate number of university students per million of the population
U.S.A.	2 918 212	175 000 000	16 670
U.S.S.R. ..	2 013 565	200 200 000	10 060
Australia ..	61 879	10 000 000	6 190
New Zealand ..	12 507	2 244 000	5 570
Canada.. ..	72 745	15 970 000	4 550
Portugal ..	22 319	900 000	2 480
United Kingdom	90 500	49 812 000	1 815

Finally I would like to make a point in favour of the English universities, for I believe that in organization and teaching they are more efficient than those in any other country that I know; this may go far to explain why we are able to graduate students in three years, whereas most other countries take four years. The length of university courses, particularly for graduate students, is continually growing all over the world. If one plots graphs showing the average age of graduation of Ph.D.'s in Harvard and the average age of retirement of professional men, the two curves appear to intersect in the year 1995; what one must infer from this remains to be seen.

Our university undergraduate courses are short but good, and many of our engineers complete their education in courses organized in industry. On the Continent, industrial training is organized for the students during their undergraduate career by the technical universities.

Dr. R. Feinberg (Manchester College of Science and Technology): From my experience in Germany as a student at two Technische Hochschulen and as an industrial research worker, and in this country as a university teacher and as an industrial research worker, I have formed an opinion as follows:

The German system has an advantage in two significant points: a student is required to have one year's practical experience before he can enter for his final examination; and the diploma thesis, for which full-time work of at least three months' duration is needed, constitutes a substantial section in the evaluation of the examination results which is important as an opportunity for the student to demonstrate his ability and initiative in a condition free from examination hazards such as nervous tension or indisposition.

The British system, instead of the four years or more required in Germany, has the advantage of a three years' course which on the whole is quite adequate, since the course is based on a more co-ordinated and comprehensive syllabus than is the case in the German system.

The young person—boy or girl—who enters a university in Britain is more mature in attitude of mind than the German counterpart. One result is that on the whole the British student is more guided by the personality of his teacher or tutor, whereas the German student is more guided by the teacher's rank, and this makes quite a difference in his development.

In research, British graduates are on the whole more capable of doing a piece of work on their own, to get their teeth into it, and to take responsibility. I cannot accept the rather pessimistic view expressed by the British team on the professional standing of students in this country; on the contrary, I feel there is something of value in the British system which commends itself and which we should not disregard.

Mr. N. Grüter (Standard Telecommunication Laboratories Ltd.): I was educated in Germany. I studied at the Technische Hochschule in Munich, and have been in this country for only a year. I should like to point out one disadvantage of the German educational system, which does not occur in England.

What first struck me when I came into contact with English engineers was the facilities offered for evening studies in schools or technical colleges. The certificates which an evening-class student can obtain in England have a very high standing and these are recognized in industry. One can obtain in evening classes a degree which is almost of the same value as that of an engineer who has followed full-time studies. This is impossible in Germany. A German who discovers his vocation for engineering at the age of twenty-five and wishes to take up a technical career, can go to evening classes and obtain some basic knowledge in a technical subject, and if he is lucky can sit for an examination for a certificate. However, this certificate is of little value. German industry considers him as somebody with a technical bias, but he would never attain status as an engineer, although in fact he might have acquired the same knowledge.

Mr. H. Clausen: I am late of the Admiralty, where I was concerned with engineering—of a kind.

I have to admit in the first instance that I have no experience whatever in teaching. I am only concerned, and have been for thirty or forty years, with the end product, and I cannot help feeling that there is a tendency in the university engineering schools to put too much emphasis on the value of what one might call the scientific and analytical side and not sufficient on the creative side—the design and the actual development work. I may be wrong, but there seems to be a generation of engineers coming along who are completely at sea in a drawing office, which is the only place where the engineer can transfer his ideas from thought to material. Whether anything can be done to raise the esteem in which drawing is held in engineering work I do not really know. The great masters, or engineers—men of the calibre of Brunel, Telford, Stephenson and others—did their own drawing. It would be a very good thing for our coming generation of engineers if part of their work was not only doing the analytical, physical mathematical side of the thing but also producing something from which manufacture could proceed without hesitation or doubt, to show that they were really engineers and not purely physicists.

Mr. F. C. Slaughter: (Glamorgan College of Technology): I have had some experience in Germany and I am extremely pleased to see this paper and report. Two things particularly interested me. The first was the reference to design, and I think that in the paper there is a statement which needs consideration: 'We think that the one respect in which the German system should be emulated is in raising the status of design in British universities.' I should like to know the attitudes of The Institution of Mechanical Engineers and The Institution of Electrical Engineers to that statement.

What do the authors feel about subjects such as railway engineering? In the Hochschulen we find a great many subjects such as motor vehicles, etc., which do not appear at all in the 'equivalent' British courses. I think that they have an intrinsic value.

The numbers carried in German schools seem much too large with the present teaching staffs, and British schools can assist German schools in the idea underlying all the laboratory courses for the fundamental subjects such as strength of materials and mechanics. From what I have seen of the laboratory courses in Germany, those for fundamentals are either missing or inadequately covered.

Mr. R. K. Turton: I am concerned with the Dip.Tech. rather than the university type of student, and I am interested in the comment which Mr. Slaughter has just made about design. The emphasis in the Dip.Tech. system is, of course, partly on practical things such as design, and there is provision in the final year in Part C for a design project. This has been variously interpreted by the Dip.Tech. people themselves, judging by the courses which have been accepted by the Council, but there seems to be much scope for the development of the scheme of the visiting lecturer from industry. One speaker said that the visiting professor in the German universities is very popular, and I think he could also be here, despite the prejudice of academic circles with regard to the interference of the industrialist.

I feel that design as practised by the actual working engineer could very usefully be transmitted in conversation in seminars etc., as well as in formal lectures. I know that many professional industrialists may find it difficult to talk to students, but I wonder whether our two major institutions, The Institution of Electrical Engineers and The Institution of Mechanical Engineers could not do some thinking on this subject. From the latter

Institution we have had a report on practical training and there is one in preparation on technical education. I wonder whether this point could be considered and whether Mr. Ashdown has some opinions on it.

Miss S. M. E. Goodfellow (Ministry of Education): I should like to say how very interested we, in the Ministry of Education, have been in watching this experiment in the exchange of information. We hope it will be the forerunner of others.

May I also counter Dr. Bowden's emphasis on the small number of university students by recalling that Government policy, admittedly after heated debate, is to rely upon the existing establishments of further education to produce a large proportion of the additional engineers and some extra scientists.

I am glad that the Dip.Tech. has been mentioned. We hope that, in due course, the technical colleges will produce 5000 qualified technologists a year by means of sandwich courses, a substantial number of them having the Dip.Tech. This is only the second year of the award, but there are increasing numbers in the first and second years and recruitment is very promising. Much depends on collaboration with industry. We believe that the Dip.Tech., combining experience and training in the works and academic work in the colleges, will produce valuable engineers.

May I take this opportunity to correct the impression given in the German report that technical colleges are conducted by the Ministry of Education. With the few exceptions of national colleges and direct-grant establishments, the technical colleges have been provided and are run by the local education authorities with the help of Government grants.

Mr. N. C. Warshaw: (Evershed and Vignoles, Ltd.): I have just returned from three and a half years in Holland, and my work has often taken me into Germany. I have had nothing whatever to do with Continental colleges at an academic level, but I have had to work with engineers from several countries. It seems that the German Dipl.-Ing., the Dutch Ingenieur and the Swiss Ingenieur, all of whose titles are protected by law, are quite distinct from our connotation of the word engineer.

There has developed, particularly in Holland and I think also in Germany, something of a mystique amongst industrialists regarding this degree—for want of a better word—of engineer. The university trained engineer in both these countries enjoys a position as a result of his academic training which is not entirely connected with his abilities, and tends, to some extent, to exclude the very able but not academically qualified engineer from the highest posts.

This is a problem in Continental industry which has been pointed out to me by several non-technical industrial executives and directors, and it is very difficult to solve. I hesitate to generalize, but I have found that in engineering application work—and I use the term in the purely English sense—the industrial engineer tends to be more useful than the academic engineer; yet many of the Continental technical college engineers whom I have come across have been surpassed in the industrial hierarchy purely because of their lack of an academic degree.

This distinction between shall we say the university engineer and the equivalent of the technical college or college of advanced technology engineer is a disadvantage of the Continental system which I should hate to see imported to this country, and I am sure that many of my Continental friends and colleagues would support this view.

Mr. R. P. Edwards (E.M.I. Electronics, Ltd.) (*communicated*): Dr. Bowden's alarming comparisons of the proportions of the population graduating from universities in the United States and Great Britain are heavily mitigated when we realize that in the American language the word 'university' covers anything from Harvard to a Mid-West collection of colleges of further education.

An oversimplified but snap comment on the paper and report would seem to be that in the matter of administering engineering education the Germans prefer their control to be at the highest level (their *Technische Hochschulen* being responsible to a *Land* Minister of Education), whereas we keep our real control for the lowest levels (the English lecturer being confined within a highly standardized course as against the German Professor who may teach how he will to students jealous of their *akademische Freiheit*). Except for this abused *Freiheit*, there is probably little need for either nation to adopt the administrative methods of the other, since each has evolved in response to national characteristics. German police, for example, are also highly controlled by *Land* Ministers of the Interior, whereas ours function under no more than watch committees.

The single sentence that most illuminates the two attitudes to the content of the engineering courses is to be found in Section 3.1 of the paper by Welbourn *et al.*: 'Whereas British universities tend to teach engineering by placing major emphasis on analysis, German technical universities lay their major emphasis on synthesis, or design.' Quite so. Yet synthesis is just what engineering is. Analysis is physics. British university engineering faculties turn out first-class applied physicists, who then acquire their engineering training piecemeal in the factory, and as a consequence never quite lose their initial bias, which is towards the belief that it is in research and not production that they will find problems of worthy intellectual calibre. Hence they crowd into the research departments, or design departments as a second best, and leave production and applications work too much to the practical fellows. Those who have recently taken up operational research or work study are startled to find that in the shop-floor and management decision-making areas there are problems worthy of the most highly theoretical thought. If the new Dip.Tech. can correct our English bias in this, it will make its greatest contribution.

Mr. D. B. Welbourn, Prof. D. B. Spalding and **Mr. G. L. Ashdown** (*in reply*): The discussion has served to emphasize the fact that, whereas many Germans envy us our educational system, many people in this country are envious of the German system. Dr. Sturley puts his finger on the weak point in our system when he mentions the difficulty of the graduate who goes into the small firm which cannot offer proper post-graduate training.

The question of the teaching of design in this country is difficult. We believe that the proper function of universities is the teaching of analysis, and that design, or synthesis, belongs properly elsewhere. We suspect that design is also subject to rational analysis; but, if so, very little has been published on the subject, and at the moment much of what passes for the teaching of design is in fact the teaching of drawing office techniques. We cannot speak for the attitudes of the Institutions to the problem; but part of the strength of the British system lies in the large number of educational experiments going on in education to-day, particularly in the Dip.Tech. courses. If research has got put on a pedestal, firms are often to blame; one of us was a foreman before he was twenty-five in a firm which believed that a university education was intended to help men to think, not to teach them the details of their professions. We do not favour the specialized courses of the German Technische Hochschulen for this and other reasons that we have given.

The experiment in general education at Berlin Technical University is having much opposition both from some members of the staff and many of the students, because it adds a year to the time at the university. The average time to graduation is steadily increasing everywhere, and this is creating a major problem which will only be solved by radical reforms.

Professor R. Wille (*in reply*): Many speakers have referred to

the problem of the numbers of engineers needed to-day. Our German technical universities are of advantage if a sudden demand for greater numbers of students arises. Lecturing to and examining great numbers of undergraduates has been accomplished successfully many times in the history of the Technische Hochschulen. It is, however, hard on the student to sit in overcrowded lecture halls and to wait for laboratory space, and we still have to find out whether the present intake of great numbers is impairing the quality of training.

Dr. Sturley mentioned the Humanistische Fakultät of the Technical University of Berlin: this institution has been working for ten years, and it is now a well-established part of the University.

It has been stated that the courses in Britain are more co-ordinated and are based on a comprehensive syllabus. We think that a student's education is rounded off if he learns about the same subject by different approaches, but this rather classical Continental way of academic teaching needs more time, and I doubt whether we shall be able to uphold it much longer.

To Mr. Warshaw I have to reply that the German 'Dipl.-Ing.' is an academic degree, and as such it is protected by law. The term 'engineer' indicating a man's profession is unfortunately neither officially defined nor protected. It is not my impression that in Continental industries preference is given to the university-trained engineer. Among the directors of our firms of all sizes one finds as many men from Ingenieurschulen as from Technische Hochschulen.

It is true that in Germany the crossing from one educational ladder to another is more difficult than in England. But great efforts are being made to improve the situation. At the Technische Hochschulen many students are to be found who have got the 'Abitur' in evening courses or who obtained admission by good marks in the final examination of an Ingenieurschule. One difficulty in the German educational system is that the young 'Abiturient', starting his higher education at a Technische Hochschule and after two years finding himself unable to pass in mathematics, cannot then transfer to an Ingenieurschule. On the other hand, this same young man may be a good practical engineer who should not have entered a course based on science and mathematics. Having this difficulty in mind I think that the new Dip.Tech.(Eng.) courses at the colleges of advanced technology are a marked achievement. Especially as sandwich courses, they are of advantage both to the men whose approach to engineering is a practical one and to the medium-size firms which cannot afford a long training for their beginners.

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THE SELECTION OF INSULATION LEVELS AND TESTS FOR HIGH-VOLTAGE TRANSFORMERS

By G. B. HARPER, Member.

(*The paper was first received 9th May, and in revised form 8th August*, 1958. *It was published in January*, 1959, *and was read before the* North-Eastern Centre *23rd March, and the* Supply Section *25th March*, 1959.)

SUMMARY

The paper reviews factors influencing the selection of transformer insulation levels, service experience on the British 132 and 275 kV Grid systems and the testing of transformer insulation.

A pattern for the overall insulation strength of a transformer, relative to service conditions, is developed from examination of test procedure, insulation characteristics, variation in voltage waveform, voltage transfer to other windings, and the influence of associated apparatus. This pattern is compared with the characteristics of protective devices, and margins between insulation and protective levels are discussed. Circumstances permitting the adoption of transformer insulation levels below those now specified are considered, suggesting that consequential capital savings for a 132 kV system would be marginal, but at higher voltages they could be significant.

A survey of service experience and fault statistics for the British high-voltage networks is made, indicating that there would be no advantage to change the present methods of surge protection.

Experience with acceptance tests is reviewed, and suggestions are made for a possible revision of insulation test procedure.

(1) INTRODUCTION

The insulation strength or insulation level of a transformer can be defined in terms of the voltage tests for which it is designed. Selection of an appropriate level depends mainly on three factors:

(*a*) The voltage of the system.
(*b*) The method of system earthing employed.
(*c*) The degree of exposure to over-voltages.

The choice therefore involves consideration, not only of the characteristics of the transformer, but also of those of the system forming part of the general problem of insulation co-ordination.

Insulation co-ordination is the process of correlation between the system characteristics, the insulation strength of its parts, and the methods adopted for surge protection, so as to achieve reasonable freedom from plant failure and supply interruption. It follows that the more efficient and reliable the protective device as a separate item of plant, the lower becomes the margin which can be tolerated between the protective level and the specified insulation strength of the apparatus.

Surge protection of transformers is usually provided either by co-ordinating rod-gaps or surge diverters. Rod-gaps, whilst inherently reliable, have the disadvantage that their protective characteristics are inconsistent and are affected, amongst other factors, by the waveshape and polarity of the surge. Furthermore, as the surge and power-follow current is directly discharged to earth, thereby resulting in a system earth fault, disconnection of the transformer, if only momentarily, is involved. Surge diverters, whilst fundamentally less reliable, provide a more uniform performance as their sparkover characteristics are controlled, and as the discharge is also controlled, system interruption is avoided. The installation of reliable surge diverters, with suitable characteristics, should therefore allow the selection of a lower transformer insulation strength than that necessary with rod-gaps. Provision of surge diverters, however, involves increased capital expenditure, and this needs to be considered relative to any possible saving from reduced transformer insulation and avoidance of plant outage.

The choice of an appropriate insulation level and degree of surge protection is also influenced by the anticipated incidence of surge over-voltage, the overhead-line characteristics of associated systems, the degree of shielding provided from direct lightning strokes and the arrangement and type of associated equipment and connections.

The object of the paper is to review the selection of transformer insulation levels with respect to the foregoing and to existing forms of voltage test. A review of experience gained with present test procedure and service experience with current insulation levels is included. Consideration is restricted to system voltages above 66 kV, since any saving resulting from reduced insulation is likely to be more significant than with lower voltages, and, in particular, to the circumstances associated with the British 132 and 275 kV Grid systems.* Effectively earthed conditions, i.e. a maximum earthing coefficient of 80%, are assumed.

(2) VOLTAGES ARISING UNDER SERVICE CONDITIONS

Service conditions involve voltage stresses of varying magnitude and duration.[1] These can be summarized as follows:

(*a*) Continuous voltage at rated frequency varying within declared limits depending on the normal operation of the system. The highest value under these conditions, termed the 'system highest voltage', is usually adopted as the basis for selection of voltage test levels. Voltages appropriate to the British 132 and 275 kV systems are 145 and 300 kV, respectively, i.e. approximately 10% above the nominal system voltage.

(*b*) Over-voltages resulting from system faults, the magnitude depending on the earthing of the system and the duration, usually limited to a few seconds, and on the form of electrical protection used. With an 80% earthing coefficient the voltage to earth would be limited to 116 and 240 kV for the 132 and 275 kV systems, respectively. This is the value adopted for the rated voltage of a surge diverter.[3] Over-voltages of a similar nature can arise owing to the sudden disconnection of a heavy load, but these normally result in a value less than that due to an earth fault although usually of longer duration.

(*c*) Internally generated over-voltages, i.e. switching surges, comprising transients of widely differing forms and a duration within the range 20–3 000 microsec.

* The principles described and the statistics given in the paper relate to the 132 and 275 kV Grid systems at present operated by the Central Electricity Generating Board (C.E.G.B.) and formerly operated by the Central Electricity Authority (C.E.A.), the British Electricity Authority (B.E.A.), and the Central Electricity Board (C.E.B.).

Mr. Harper is with the Central Electricity Generating Board.

(*d*) Atmospheric over-voltages, i.e. surges resulting from lightning strokes, of widely differing forms but usually with a steeper wavefront than (*c*) although of shorter duration.

The magnitude at the terminals of the apparatus both for (*c*) and (*d*) depends on the characteristics of the system and the level of surge protection provided.

(3) INSULATION CHARACTERISTICS OF TRANSFORMERS

(3.1) Transformer Insulation Tests

The insulation level of a transformer is usually designated by the full-wave (1/50 microsec) impulse test voltage for which the windings are designed. Associated with the impulse test level there is a power-frequency voltage test of specified duration equivalent to one minute. The latter is included in present specifications as a routine test, and the former as a type test. For windings with graded insulation normally employed under effectively earthed conditions where the separate-source power-frequency test voltage is limited by the insulation at the neutral end of the winding, the specified value is applied as an induced voltage. This practice differs from that for windings with uniform insulation where a separate-source voltage is used for testing the insulation to earth and between phases, the induced test being confined to inter-turn, inter-coil conditions. Test voltages at present specified for the 132 and 275 kV systems, together with values appropriate to an insulation level one step lower, are shown in Table 1. The corresponding separate-source test voltage for both cases is 45 kV.

Table 1

TRANSFORMER TEST LEVELS

Full-wave impulse test level kV (peak)	Power-frequency test voltage kV (r.m.s.)
450	185
550*	230
900	395
1 050*	460

* Values at present specified.

The voltage distribution within the windings and to earth resulting from the tests differs considerably depending on the form of test.

(3.2) Voltage Distribution under Power-Frequency Test Conditions

During power-frequency voltage applications the voltage distribution can be considered as uniform between turns and coils and evenly distributed to earth, the potentials to earth depending on the test connections employed.

(3.3) Voltage Distribution under Impulse Test Conditions

The voltage distribution within the windings and to earth under impulse test conditions depends on the form of application. Present British practice covers two forms, namely, (*a*) full waves, where the applied voltage discharges naturally through the winding to earth, and (*b*) chopped waves, where a voltage wave (1/50 microsec) is collapsed on the wavetail across a rod-gap or similar device. A further form of application included in American practice is a front-of-wave test, where a particular rate of rise of voltage is specified such that the use of a rod-gap similar to that for chopped waves results in collapse on the wavefront.

Full-wave applications demonstrate the ability to withstand surges, which, although limited to a safe value by protective devices, are not subject to complete or sudden collapse. These conditions are approached by the correct operation of a surge diverter. Chopped-wave applications demonstrate the ability to withstand the modified stresses caused by a sudden collapse of the surge, assuming that the rate of rise of voltage is such that the chop occurs on the wavetail, as may result from co-ordinating rod-gap operation. The front-of-wave test covers similar conditions with steep-fronted waves.

(3.3.1) Full-Wave Voltage Applications.

The voltage distribution resulting from a full-wave application is, to a great extent, controlled by the ratio of the shunt-to-series capacitance of the winding.[4, 5] This ratio governs the distribution arising immediately on application of the impulse, and consequently the amplitude and duration of any oscillations occurring within the winding and to earth, until the impulse is finally discharged.

(3.3.2) Chopped-Wave Voltage Applications.

Collapse of the impulse on the wavetail, owing to the sudden rate of change of voltage, results in increased inter-turn and inter-coil stress, although voltages to earth are usually reduced.

Although the insulation level of a transformer is designated in terms of the full-wave voltage, the present procedure for chopped waves involves the application of a voltage increased by approximately 15%, so that the chop occurs without undue delay when a gap setting, equivalent to a 50% flashover at the full-wave level, is employed. The combination of gap setting and increased voltage usually results in a chopping time of between 3 and 6 microsec. Examination of impulse-voltage/time-to-breakdown curves for typical transformer insulation (see Fig. 1)

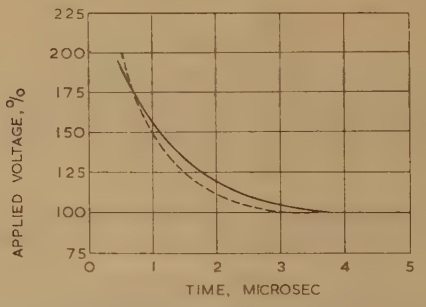


Fig. 1.—Impulse-voltage/time curves for typical transformer insulation structures.
——— From Reference 2.
- - - - From Reference 6.

suggests that, after approximately 3 microsec, the curve flattens which implies enhanced insulation strength over that required for the specified full-wave level. As a conservative estimate therefore, it is suggested that the result of the increased voltage for the chopped-wave test represents an increase in insulation strength of at least 10%.

(3.3.3) Front-of-Wave Voltage Applications.

The test involves the application of a still higher voltage to the line terminal. In view of the shorter duration, however, the increased stress is confined to the entrance insulation; and the internal voltages developed are usually less than those arising from chopped waves.

Consideration of the voltages specified, compared with the curves of Fig. 1, suggests the inherent capability of transformer insulation to withstand the applied impulse for the shorter durations involved. This is supported by the figures in Table 2 where the ratio of voltages included in American specifications based on a rate of rise of 1 MV/microsec, relative to those fo

Table 2

RATIOS OF CHOPPED WAVE TO FRONT-OF-WAVE VOLTAGE

Full-wave test level	Chopped-wave test level	Front-of-wave minimum	Time to sparkover	Ratio of chopped wave to front-of-wave voltages	
				Test values	Fig. 1
kV (peak)	kV (peak)	kV (peak)	microsec		
450	520	710	0·71	1·37	>1·5
550	630	825	0·825	1·31	>1·5
900	1035	1240	1·24	1·20	1·35
1050	1210	1400	1·40	1·16	1·30

the chopped-wave test, based on a 15% increase over the full-wave level associated with a minimum time for gap flashover of 3 microsec, are compared with corresponding ratios deduced from Fig. 1.

(3.4) Effect of Variation in Waveform

Variation in waveform of the applied impulse results in modification to the voltage distribution developed both for conditions to earth and between turns and coils.[7]

Decrease in the steepness of the wavefront results in a general reduction of the internal stress both at the line end and in the body of the winding. The voltages to earth throughout the winding are practically unaffected, although there is a tendency to reduce the concentration of stress on the entrance insulation. Shortening of the wavetail, other than when a chop occurs, has little effect on either the voltage to earth or the internal stress at the line end, whilst both, and particularly the former, are reduced in the body of the winding. Longer wavetails tend to increase the voltage to earth, but their effect on internal stress is usually negligible.

(3.5) Deduced Insulation Strength with respect to Internally Generated Over-Voltages

Although the different forms of impulse voltage demonstrate the ability to withstand surges of an atmospheric origin, no corresponding test is at present specified to demonstrate the insulation strength with respect to internally generated over-voltages. Owing to their longer duration, these involve stresses somewhere between those arising under impulse and power-frequency test conditions.

However, various studies have been made on typical insulation structures and on complete transformers[8,9] with the object of determining this strength relative to existing forms of test. On the basis of a voltage wave rising to a peak value in 1–4 millisec, it has been deduced that the insulation switching surge strength can be safely assumed as equivalent to 1·3 times the peak value of the power-frequency voltage, or 80% of the full-wave impulse level. A comparison of deduced insulation switching surge strength is shown in Table 3.

As the values in Table 3 are derived from the full-wave impulse level, any increase in the insulation strength required by the chopped-wave test (Section 3.3.2) will also result in added margins.

(3.6) Apparatus Directly Connected to the Transformer Winding

For a comprehensive assessment of the overall insulation strength of a transformer, consideration must also be given to the characteristics of apparatus directly connected to the winding, i.e. bushing insulators and voltage-regulating equipment.

Table 3

DEDUCED TRANSFORMER INSULATION SWITCHING SURGE STRENGTH

Full-wave impulse test level	Power-frequency test voltage	Deduced switching surge strength	
		Column 1 × 0·80	Column 2 × √2 × 1·30
kV (peak)	kV (r.m.s.)	kV (peak)	kV (peak)
450	185	360	340
550	230	440	425
900	395	720	725
1050	460	840	845

(3.6.1) **Bushing Insulators.**

The insulation characteristics of a bushing differ from those of the transformer winding in that:

(*a*) The impulse-voltage/time characteristics for a duration less than 3 microsec indicate a relatively higher insulation strength.
(*b*) The impulse ratio is usually lower and tending to approach that of a rod-gap (approximately 1·5 against 2·2).
(*c*) As air insulation is involved the external impulse flashover is affected by the polarity of the surge.
(*d*) The insulation characteristics are affected by atmospheric conditions, e.g. pollution and rain.

The influence of the foregoing is shown by the tests specified for the bushing as a separate component in B.S. 223 (Reference 10). However, as the bushing forms part of the entrance insulation to the transformer, increased insulation margins relative to the protection level may be desirable, and adoption of reduced insulation levels merits special consideration in this respect.

(3.6.2) **Voltage-Regulating Equipment.**

The voltage stresses involved are those to earth and between contacts of the switching apparatus, the former depending on the point of the winding to which the switch is connected and the latter on voltages developed in and across the tapping winding. Insulation requirements for the voltage-regulating equipment must therefore be considered in relation to the associated transformer winding.

With graded insulation the voltage-regulating equipment is usually connected to tappings at the neutral end of the winding. The maximum voltage to earth under normal conditions is equal to that of the tapping range, and the voltage between contacts is equal to that of the tap-step voltage or tapping range, depending on the contacts considered and the contact arrangement. Under power-frequency test conditions the voltage to earth depends on the test connections, the voltage between contacts being proportional to the test voltage supplied. Under impulse test conditions both the maximum voltage to earth and the voltage between contacts depends on the voltage distribution developed by the winding, which is influenced by the design of the winding and the physical position of the tapping winding.

An exception is the case of an auto-transformer with tappings at the junction of the series and common winding when part of the switch forms the lower-voltage terminal and has to be designed to withstand directly applied impulse voltages.

Impulse-voltage considerations usually dictate the insulation requirements of the regulating equipment, and, in certain designs, non-linear resistance shunts or special surge diverters are employed to reduce the voltages which would appear between contacts and across the switch.[11,12]

As the stresses are controlled by the winding design, no simple set of tests can be formulated to cover all conditions. Present test procedure, therefore, does not include routine dielectric tests

on the switch; the equipment is tested as an integral part of the transformer. In practice, however, design limits are assigned to the switch, implying selection of a suitable winding design. Considering impulse tests on the complete transformer, the stresses developed within the winding can be influenced by the tapping to which the switch is connected. As the tapping position which results in the more onerous distribution is not necessarily that which imposes the highest stress on the switch, unless there is definite evidence to support the selection of a particular position, the test is conducted with the regulator on normal ratio.

(3.7) Voltage Transfer to other Windings

Consideration has so far been limited to the stress resulting from voltage application to one winding. In practice, however, there is always at least one other winding on the same limb of the transformer.

When an impulse is applied to the terminal of one winding, voltage can be transferred to other windings, both electrostatically and electromagnetically, owing to the coupling between the windings.[13–15] At the instant of application, the transfer is controlled by the capacitive coupling in a manner similar to that governing the initial impulse distribution (Section 3.3.1), followed by an electromagnetic transfer proportional to the turns ratio of the transformer and the relevant voltage conditions. Any external load on the transformer terminals, however, results in considerable modification of the transferred voltage, and under service conditions the effect of the surge impedance of associated connections is usually sufficient to reduce the magnitude to a safe value. The electromagnetically transferred component is usually more severe than the electrostatically transferred voltage peaks.

A possible exception applies in the case of a machine directly connected to the lower-voltage terminals of the transformer, when the maximum value of the transferred voltage may be high relative to the recognized insulation strength of the machine.[16, 17]

Special consideration may also be necessary for an auto-transformer, where conditions are generally more severe than those for a double-wound unit, and where, under open-circuit conditions, the transferred voltage can considerably exceed the applied voltage wave.[18, 19]

(3.8) Summary

The overall insulation characteristics of a transformer as demonstrated by the various forms of impulse and power-frequency voltage test, combined with deduced switching surge strength and service voltage conditions for the test levels given in Table 1, are illustrated in Fig. 2.

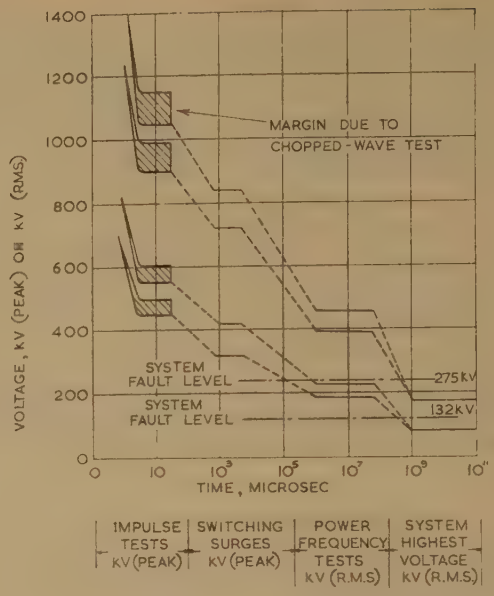


Fig. 2.—Transformer insulation characteristics.

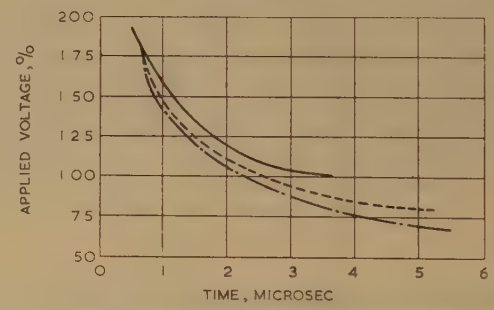


Fig. 3.—Comparison between impulse-voltage/time curves for rod-gaps and transformer insulation.

——— As for full-line curve of Fig. 1.
– – – – Rod gap, negative polarity.
—·— Rod-gap, positive polarity.

Rod-gaps are based on a setting for an 80% protective level.

(4) CHARACTERISTICS OF PROTECTIVE DEVICES

(4.1) Co-ordinating Rod-Gaps

The protective level provided by a rod-gap is directly related to the breakdown strength of the air-gap, and is therefore affected by the polarity of the applied surge, the mounting arrangement of the gap, the electrode shape and varying atmospheric conditions.

A typical voltage/time characteristic for a rod-gap[20] is illustrated in Fig. 3, and is compared with a similar curve for transformer insulation on the basis of the latter representing a 100% level and the former an 80% protective level. The difference in the two characteristics demonstrates the higher flashover voltages of a rod-gap for short-time durations and the reduced margin in the case of steep-fronted impulse waves.

In considering rod-gap settings due account should be taken of the wide dispersion in flashover.[21] Under service conditions one electrode is always at a potential above earth, and there is therefore the possibility of corona discharge from the tip. The possibility of this discharge acting as a stabilizing agent, thus reducing the dispersion, has been investigated but found to have no practical effect. The effect of fitting small spheres to the end of the electrodes to reduce radio interference has also been investigated, but similarly no practical difference in the characteristic was evident.

(4.2) Surge Diverters

Owing to the characteristics of material used in its construction (silicon carbide) a surge diverter has a limited and critical thermal capacity. It is therefore essential that operation, i.e. sparkover of the gaps with consequent current discharge, should not occur during either normal or abnormal increase in the system voltage. For this reason, the recommended voltage rating of the diverter is in terms of the maximum voltage to earth attained under system fault conditions,[3] and depends on the method of system earthing employed.

The protective characteristics, as demonstrated by tests on the surge diverter, comprise the following:

(*a*) Front-of-wave impulse sparkover, indicating the operating level relative to a specified rate of rise of voltage.

(*b*) Impulse sparkover, indicating the operating level relative to a 1/50 microsec wave.

(*c*) Residual discharge voltage indicating the voltage level after gap operation relative to a specified discharge surge current.

(*d*) Dry power-frequency sparkover voltage indicating the operating level relative to voltages allied to system voltages. This value also gives a measure of the protective level with respect to long-duration switching surges.

(5) SELECTION OF SURGE PROTECTION AND THE INFLUENCE ON TRANSFORMER INSULATION LEVELS

(5.1) General

Choice of co-ordinating rod-gap protection involves consideration of two interrelated requirements:

(*a*) Whether the arrangement of the system is such that earth faults consequent upon gap operation can be tolerated without prejudice to continuity of supply.

(*b*) If the circumstances in respect of (*a*) are satisfactory, whether the protective level available offers reasonable security against plant failure.

When the system conditions are such that either of these cannot be achieved, the provision of surge diverters is essential.

Effective surge protection requires a reasonable safety margin between the specified insulation level of the transformer and the operating level of the protective device. Whilst this margin will depend on the type and location of the device, a value of 20%, i.e. 80% protective level, at the terminals of the transformer is usually recommended. Rod-gap settings and surge-diverter rated voltages, corresponding to this margin, for the transformer insulation levels covered by Table 1, together with the nearest standard diverter ratings given in B.S. 2914, are shown in Table 4.

Table 4

PROTECTIVE LEVELS

Full-wave impulse test level	Protective level 80% value	Rod-gap setting Negative wave	Rated voltage of diverter	
			Derived from B.S. 2914	Nearest Standard B.S. 2914
kV (peak)	kV (peak)	in	kV (r.m.s.)	kV (r.m.s.)
450	360	18	100	100
550	440	22	122	123
900	720	39	198	196
1 050	840	46	232	245

Col. 4 is based on residual discharge voltages derived from B.S. 2914.
Recommended diverter rated voltages for system highest voltages of 145 and 300 kV are 116 and 245 kV, respectively.

Although the values given in Table 4 may represent a desirable protective level, practical considerations could dictate otherwise, and the real criterion of a reasonable safety margin depends on satisfactory operating experience.

With rod-gap protection any desired safety margin can be achieved by the simple expedient of reducing the electrode spacing. Lower settings, whilst providing improved protection, involve more frequent gap operation in the majority of instances as the result of over-voltages of a harmless magnitude, e.g. low-order switching surges. Similar circumstances apply to an assessment of a safety margin for steep-fronted waves (see Fig. 3), where a setting which provides protection against all forms of wave may lead to an unacceptable degree of gap operation. Selection of an appropriate setting must therefore be a compromise between a value which is theoretically desirable and one which, whilst providing an acceptable, if inferior, level of protection, does not result in operational embarrassment.

The amplitude and form of surge voltages of an atmospheric origin arriving at the terminals of the transformer, however, are controlled to a considerable extent by the substation connections, and the degree of shielding provided both in the substation and on associated overhead lines.[22] These extenuating conditions and consideration of the anticipated incidence influence the acceptable level of protection and consequently the choice of gap setting.

For transformer insulation levels below the values at present specified (see Table 1), the gap settings necessary to provide even the narrowest safety margin would indicate that the adoption of reduced levels associated with rod-gap protection is impracticable.

With surge diverters the same freedom of choice of safety margin is not available, and the selection of a protective level is limited, not only by standard voltage ratings, but also by the diverter characteristics. For the transformer insulation levels at present specified, recommended diverter voltage ratings and characteristics based on B.S. 2914 provide safety margins of 24 and 16% for levels of 550 and 1 050 kV(peak), respectively. Considering transformer insulation levels reduced by one step, i.e. 450 and 900 kV(peak), the recommended diverter ratings would provide safety margins of 7 and 2% respectively, which are insufficient for satisfactory operation. To provide a 20% safety margin, system conditions corresponding to earthing coefficients of 69 and 65% would be necessary, and these, even under the most favourable circumstances, are unlikely to be achieved. The adoption of transformer insulation levels below the values at present specified would therefore involve the provision of surge diverters having better characteristics than those given in B.S. 2914.

The possibility of adopting reduced transformer insulation levels associated with the use of suitable surge diverters has received considerable attention in the United States[8, 9] and some service experience has been gained under conditions which permitted the installation of diverters with a rated voltage corresponding to an earthing coefficient[23, 24] of 75%. Protective levels derived from B.S. 2914 for diverter ratings corresponding to a 75% earthing coefficient give safety margins of 11 and 9% for insulation levels of 450 and 900 kV (peak), respectively. The values given in B.S. 2914, however, represent maxima, and, in practice, suitable diverter ratings may be available which offer a more acceptable protective level.

As a manufactured item of plant, owing to the comparative complexity of design and the type of material used in its construction, a surge diverter cannot be regarded as entirely free from fault incidence. Statistics based on service experience applicable to modern diverters suggest a possible rate of failure[25, 26] of 0·4 and 0·6%. Furthermore, under conditions of severe atmospheric pollution, external contamination on the surge-diverter weathershield can disturb the voltage grading across the gap assembly,[27, 28] and with multi-unit constructions the voltage distribution between units, to an extent that certain designs may be unsuitable for installation in dirty locations. Provision of surge diverters also implies an added maintenance liability. Where marginal advantages favour the choice of surge-diverter protection, these factors may have a significant bearing on the final selection.

(5.2) Economic Consideration

The main advantage to be gained from the adoption of lower transformer insulation levels is the possible saving in capital expenditure and operating costs owing to reduced losses.

Possible price variation for transformer insulation levels estimated from the general structure of current British transformer prices is shown in Fig. 4. The percentage reduction in price for lower insulation levels will tend to decrease with increase in apparent-power rating, and the variation illustrated

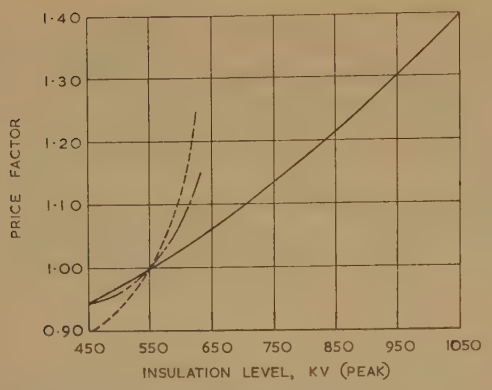


Fig. 4.—Variation of price with insulation level.
——— British prices.
– – – – American prices, 30 MVA (Reference 23).
—·— American prices, 100 MVA (Reference 23).

is therefore only approximate. This latter point is demonstrated by the broken curves in Fig. 4, which are taken from transformer prices published in the United States.[23] Due allowance should be made in comparison between the curves for the different factors which influence the price, e.g. regulating equipment, type of cooling, loss ratio and impedance.

Estimated savings for reduced insulation levels as a percentage of the transformer price for different ratings and voltage levels based on British conditions, including provision of surge diverters in place of rod-gaps, are illustrated in Fig. 5, from which it can

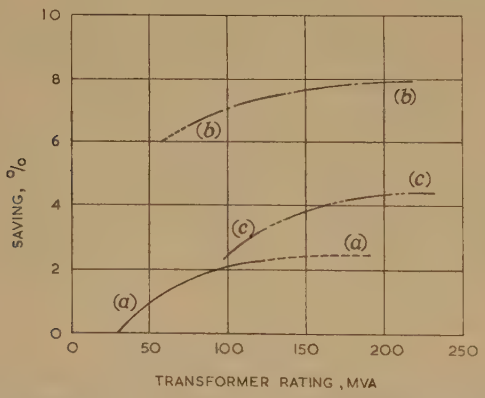


Fig. 5.—Saving as a percentage of transformer price for reduced insulation levels associated with provision of surge diverters.
(*a*) 132 kV double wound.
(*b*) 275 kV double wound.
(*c*) 275/132 kV auto-connected.

be seen that, although savings applicable to the 132 kV system are marginal, those in respect of the 275 kV system could be significant. No allowance has been made in Fig. 5 for reduced transformer loss, any possible saving being offset against the added maintenance and fault liability associated with the surge diverter.

A further advantage which could result from lower insulation levels is a possible reduction in the transport weight of the transformer; this is an important consideration with large high-voltage units.

Whilst the foregoing illustrates economies resulting from adoption of lower levels, it should be emphasized that these can be achieved only when system conditions permit the use of suitable surge diverters. Furthermore, it is suggested that extensive experience with surge-diverter protection, allied to the particular service conditions, is desirable before the adoption of lower insulation levels is contemplated.

(5.3) Service Experience under British Conditions

The following principles are adopted for the surge protection of transformers associated with the 132 and 275 kV Grid systems:

(*a*) For substations connected directly to steel-tower lines fitted with earth wires, where the installed capacity is usually such that disconnection of one transformer does not prejudice continuity of supply, co-ordinating rod-gaps are provided with a setting of 26 in for the 132 kV Grid system and 48 in for the 275 kV Grid system.*

(*b*) For transformers connected to wood-pole lines without earth wires, surge diverters are provided.

(*c*) For transformers directly connected to the terminals of a generator, surge diverters are provided to avoid loss of output and the effect of abrupt loss of load on the steam plant.

(*d*) No surge protection is provided for the lower-voltage windings of transmission transformers below 132 kV or for the lower-voltage windings of generator step-up transformers.

Variations to the above principles apply in a few cases where local circumstances merit other considerations.

Protective levels provided by rod-gap settings of 26 and 48 in, for the specified transformer insulation levels, are illustrated in Fig. 6.

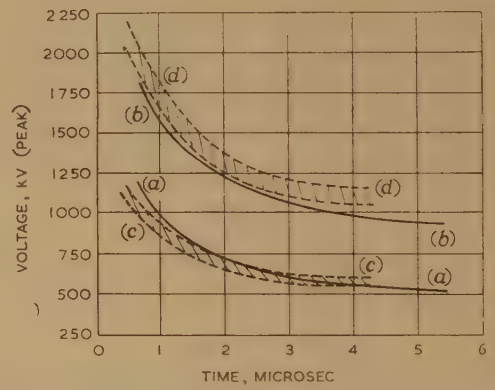


Fig. 6.—Protective levels, 26 and 48 in rod-gaps, relative to 550 and 1 050 kV(peak) transformer insulation levels.
(*a*) 26 in rod-gap, negative wave.
(*b*) 48 in rod-gap, negative wave.
(*c*) 550 kV (peak) insulation level.
(*d*) 1 050 kV (peak) insulation level.
The extra insulation strength due to the chopped-wave test is shown as 10% margin.

Transformer fault statistics for the period 1934–47, relating to the 132 kV system, indicate an average rate of winding failure of one transformer per year, which, expressed in terms of faults per 100 transformers per annum, amounted[29] to 0·28. Similar statistics, subdivided into faults resulting from lightning and switching operations, for the period April, 1948, to March, 1958, are given in Table 5.

With reference to lightning faults, apart from two incidents, all the transformers involved were manufactured prior to 1939, and their insulation strength can be considered inferior when compared with modern designs. Of the two incidents with later designs, one involved a transformer connected to a 'teed-feeder', where available evidence indicated a direct lightning stroke on the substation resulting in damage to the windings of two phases and flashover of the associated rod-gaps. The circumstances of the second incident concerned tripping of the transformer as the result of a stroke some distance from the substation. Thorough internal examination and tests revealed no evidence of damage, and the transformer was returned to service, followed, after an

* The setting for the 275 kV Grid system is provisional pending further service experience and the gaps provided are adjustable between 46 and 52 in.

Table 5

TRANSFORMER FAULT STATISTICS

Year	Type of fault	
	Lightning	Switching
	Number of transformers involved	
1948–49	2	—
1949–50	—	—
1950–51	5	3
1951–52	—	—
1952–53	—	—
1953–54	1	—
1954–55	1	1
1955–56	—	2
1956–57	1	—
1957–58	3	1
TOTALS	13	7

interval of ten days, by a severe fault in the region of the tap-changing equipment. Any conclusive evidence as to the origin of the fault was destroyed, but damage to a bushing in the tap-changer resulting from the lightning incident was suspected. With regard to other lightning incidents, faults recorded for the period 1957–58 include failure of two transformers over 25 years old, recently installed at the same substation without any form of surge protection, and one fault during 1950–51 involving a transformer connected to a 'teed-feeder', providing a temporary supply, where the available evidence again indicated a direct lightning stroke. In the latter case damage was confined to an internal flashover from the line termination to the tank wall.

Considering faults due to switching operations, four incidents involved internal flashovers between inter-phase lower-voltage (delta) connections, during switching from the high-voltage side of unloaded transformers. Three of the transformers involved were of similar design. These incidents emphasize the need for adequate clearances between inter-phase delta connections. Of the three remaining incidents, two involved identical transformers installed at the same substation, where flashover in the tap-changing equipment occurred coincident with switching on the 132 kV system from a remote point, one during 1950–51 and the second during 1955–56. The remaining incident involved a transformer manufactured in 1930 and resulted in an inter-turn h.v. winding fault.

Expressed as faults per 100 transformers per annum, the incidents recorded in Table 5 amount to an average of 0·25 in respect of lightning and 0·13 in respect of switching operations. A corresponding figure covering all winding faults, i.e. including incidents unassociated with lightning or switching, but excluding faults due to lightning or switching which did not result in a winding fault, amount to 0·34. This latter figure is comparable with the value of 0·28 referred to in Reference 29. As some 250 transformers installed on the 132 kV system are now over 20 years old, it is to be expected that the rate of fault incidence will tend to increase.

A more quantitative assessment of the overall performance can be made from consideration of the non-availability factor, which is defined as

$$\frac{\text{Number of hours lost through transformer outages} \times 100}{\text{Total number of transformers installed} \times \text{hours per annum}}\ \%$$

For a representative period (1949–55) the average non-availability factor estimated on the basis of all transformer faults (a fault being defined as any incident in the zone covered by the transformer protection which involves disconnection of the transformer), whether due to the transformer, associated connections or maloperation, amounted to 0·471%.

Assuming all faults associated with lightning and switching, including rod-gap operations, could be prevented by the installation of surge diverters, it is estimated that this factor would be reduced to 0·37%. This improvement, when considered with the possible rate of fault incidence associated with surge diverters[25, 26] and the fact that, in general, no interruption of supply is involved, does not justify any change in the method of surge protection. Furthermore, it is estimated that the cost of providing surge diverters for all transformers installed on the 132 kV transmission system would amount to more than three times the cost involved in repair of transformer damage.

The relatively low fault rate experienced with lightning and switching, however, cannot be taken as a direct criterion of the efficiency of rod-gap protection, and due account must be taken of the system circumstances and performance as a whole. A measure of the overall performance is demonstrated by the figures given in Table 6, which show that, compared with an approximate annual average of 60 circuit interruptions, rod-gap operations amount to an annual average of 4.

Table 6

COMPARISON BETWEEN THE NUMBER OF CIRCUIT INTERRUPTIONS DUE TO LIGHTNING AND TRANSFORMER ROD-GAP OPERATIONS

Year	Number of circuit interruptions	Transformer rod-gap operations	Ratio of col. 2 to col. 3
1948–49	71	7	10
1949–50	52	3	17
1950–51	36	3	12
1951–52	48	2	24
1952–53	83	8	10
1953–54	65	3	22
1954–55	33	2	16
1955–56	54	6	9
1956–57	75	3	25
Average	57	4	14

These statistics exclude both generator transformers and transformers associated with the 275 kV system. The fault incidence in the categories considered, i.e. lightning and switching, is zero.

In isolated cases, during examination of old transformers, evidence of inter-turn insulation damage in the form of pin holes has been found, presumably resulting from lightning incidents where puncture has occurred without the development of a power fault.

(6) TRANSFORMER INSULATION TESTS

(6.1) Present Test Procedure

As stated in Section 3.1, the present specified procedure covers two types of voltage test, namely impulse and power frequency.

(6.1.1) Impulse Voltage Tests.

Two forms of voltage application are involved, namely full wave (Section 3.3.1) and chopped waves (Section 3.3.2). The sequence of voltage applications comprises (*a*) one full wave at the specified level, followed by (*b*) two chopped waves at approximately 15% above the specified level, followed by (*c*) two full waves at the specified level.

Oscillograph records of all applied voltage waves are required together with, for the full-wave voltage applications, some form of supplementary record covering the current flowing directly to earth (neutral-current method), the current flowing to earth via the tank (line-current method), or the voltage transferred to another winding.[30–33] Similar records are taken at a reduced voltage to provide a reference for fault detection.

A criticism of the chopped-wave test has been the lack of evidence that failure has not occurred.[34] The only available record is the voltage wave up to the time of chop, which excludes the period of high internal stress developed as the result of the chop. Reliance in the past has therefore been placed on any damage being revealed by the subsequent full-wave applications, which, owing to the different form of stress involved, is not entirely satisfactory.

However, recent improvements have resulted in test techniques whereby the time to chop is controlled,[35] thus permitting supplementary records precise in form. As these techniques include forms of triggered gaps, the need for an increased voltage disappears, and adoption of a revised test procedure on this basis could imply an insulation strength lower than that required by the present procedure (Section 3.3.2). Whilst these improved techniques with enhanced fault detection are welcome, the consequences of reduction in the applied voltage need to be considered in relation to experience with existing levels and the effect on the transformer price (Fig. 4).

Although not mandatory, certain test departments record supplementary waves during chopped-wave applications when normal rod-gaps are employed. These records, whilst not identical unless the chopping times are extremely close, bear a similar resemblance, and with experienced interpretation can be a useful aid to fault detection.

A difficulty often experienced during the testing of large transformers is maintenance of the waveshape within the tolerance permitted by B.S. 923,[36] owing either to the low-inductance or high-capacitance load of the windings. In such cases it is usual for other conditions to be agreed between the manufacturer and purchaser, but it should be noted that increased tolerances tend to less onerous test conditions[37] (Section 3.4). In this respect the waveshape used in American practice, 1·5/40 microsec, is less onerous that that required by B.S. 923.

(6.1.2) Power-Frequency Voltage Tests.

Two forms of application are again involved, namely separate source and induced voltage. Owing to the form of the test and in comparison with impulse-testing techniques, the possibility of fault detection leaves much to be desired. This is only evident by collapse of the supply voltage or aural indication from the transformer, unless a gas relay (Buchholz) is fitted, which is a procedure strongly to be recommended. B.S. 171[38] permits the time of application to be reduced for test frequencies greater than 100 c/s, subject to an equivalent duration of 6000 cycles and a minimum time of 15 sec. Whilst this reduction may be logical from consideration of the insulation characteristics,[39] in view of the limitations with respect to fault detection the full duration of one minute is preferred.

(6.2) Experience with Acceptance Tests

Although basically intended as a proof of design, the impulse test provides a searching check on materials, processing and workmanship. For this reason a policy of testing one transformer in every ten manufactured was adopted by the British Electricity Authority and has since been continued. The results of this programme are summarized in Table 7.

In no case could failure be attributed to fundamental design weakness, and, in many instances, earlier tests witnessed on prototype windings had shown adequate margins over the specified level. The one failure in respect of workmanship involved misplaced winding packing. General improvement resulting from attention to weakness in materials and processing revealed by the test is worthy of note.

Table 7

Results of Impulse Test Programme

Year	132 kV			275 kV	
	Total tested	Number failed	Code	Total tested	Number failed
1950	3	2	(1) P—(1) M	—	—
1951	3	1	M	—	—
1952	8	2	(1) W—(1) M	1	—
1953	2	—	—	—	—
1954	2	1	P	3	—
1955	10	1	P	3	—
1956	8	—	—	1	—
1957	12	1	M and P	3	—
Totals	48	8	—	11	—

P. Failure due to inadequate processing.
M. Failure due to flaws in material.
W. Failure due to workmanship.

The small degree of damage found in many instances during the investigation of failures demonstrates the general reliability and sensitivity of the fault-detection techniques. For ease of interpretation it is considered essential that separate oscillograms be provided for each impulse application, covering both voltage and supplementary records.

With reference to power-frequency tests, failures experienced during the corresponding period have been negligible. Three winding faults, however, have occurred shortly after commissioning, for which no satisfactory explanation has been established. Two involved 132 kV windings and one a 33 kV winding; in each case the evidence suggested commencement as an inter-turn fault. These faults, together with an additional incident resulting from ingress of moisture during erection, amount to approximately 1% of the total number of units installed during the period.

(6.3) Future Revision of Test Procedure

Three forms of over-voltage can arise under service conditions, namely atmospheric, those due to switching operations and over-voltages resulting from system faults.[2] Impulse tests associated with a suitable protective level correspond to the first of these. Power-frequency tests, however, bear no equivalent relationship. Present values result in margins of 100 and 92% with respect to system faults levels, 60 and 65% applying in the case of levels reduced by one step (see Fig. 2). A more logical approach would therefore be replacement of the present power-frequency test by two tests, complementary to the impulse test, one corresponding to switching over-voltages and the other to system fault levels. As the impulse test is at present a type test, power-frequency tests provide, in the majority of cases, the only qualitative check on the transformer insulation. Any revision of test procedure must take account of this fact to the extent of introducing impulse tests on a routine basis.

With regard to power-frequency tests, the reduction of present values to one which provides a reasonable margin over the system fault level would permit a longer duration of application, which, in turn, could prove advantageous as a qualitative check on production, without involving the same degree of risk of undetected damage. In conjunction with a suitable test simulating

switching conditions, the reduced power-frequency test would leave the designer free to develop an insulation structure directly related to system requirements without possible anomalies dictated by arbitrary values.

When future consideration is being given to the revision of transformer insulation tests, therefore, the following procedure may merit examination:

(*a*) Impulse tests on a routine basis.
(*b*) A suitable test corresponding to switching over-voltage conditions, if necessary, as a type test.
(*c*) A reduced power-frequency test, showing a reasonable margin over the system fault level for a longer duration, as a routine test.

The adoption of the above procedure would depend on acceptance of (*a*), in which case improvements in techniques to reduce the time required for the test and the cost would be essential. Furthermore, unless a suitable form were devised for (*b*), it would be imprudent to lower present power-frequency values, although a minimum duration of one minute, irrespective of the test frequency, deserves consideration.

(7) CONCLUSIONS

The adoption of transformer insulation levels below those at present specified (Table 1), provided that reliable surge diverters with suitable characteristics are available and system conditions permit their use, should result in some capital saving. On the basis of British conditions and prices, it is estimated that, whilst any saving with system voltages approximating to 132 kV would be marginal, savings for higher-voltage systems could be significant. Before adoption of lower transformer insulation levels is contemplated, however, it is suggested that extensive service experience with the use of surge diverters is desirable.

Examination of service records and fault statistics applying to the 132 and 275 kV Grid systems (B.E.A., C.E.A. and C.E.G.B.) indicates that no advantage would be gained from a change in policy with regard to the methods of surge protection employed. The relatively low fault rate, however, cannot be taken as a criterion of the efficiency of protective devices directly associated with the transformer, e.g. co-ordinating rod-gaps, and due account must be taken of system circumstances as a whole.

Present procedure for the chopped-wave impulse test results in a transformer insulation strength at least 10% greater than that required by the full-wave level. The introduction of any improved chopped-wave testing technique which could involve limitation of the voltage applied to that of the specified full-wave level, thus reducing this margin, needs to be considered with respect to service experience and the effect on the transformer price. Any such reduction could also influence the adoption of lower transformer insulation levels. For example, considering the change from 550 to 450 kV(peak) (82%), elimination of the margin due to a change in test procedure would result in an effective reduction in insulation strength to 75%.

Consideration of voltages arising under service conditions relative to present transformer insulation tests would suggest that a more logical pattern could be obtained by the reduction of the present power-frequency voltages, subject to the introduction of impulse voltage tests on a routine basis and an additional test covering switching over-voltages.

(8) ACKNOWLEDGMENTS

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DISCUSSION BEFORE THE SUPPLY SECTION, 25TH MARCH, 1959

Mr. E. C. Rippon: Practical operating experience with the British Grid system strongly suggests that the incidence of surges of atmospheric origin is small and that, when surges do occur, they do not approach the severity of the standard impulse wave of 1/50 microsec. The low transformer fault rate recorded during the last ten years confirms this, and, by inference, also confirms the general policy to use rod-gaps as the sole surge protection on the 132 and 275 kV transformers. However, if lower insulation levels are contemplated, it would be imprudent to install such transformers without surge diverters.

The economic advantages of transformer protection with surge diverters is discussed in the paper, and, even at 275 kV, it is problematical whether any very definite saving can be achieved. A more important contribution which might arise from the use of surge diverters, is the possibility of designing larger outputs of 3-phase transformers, capable of transport. Any such application will show a very large capital saving, i.e. the difference in cost of equivalent transformer capacity, in two 3-phase or separate single-phase units, and the cost of a 3-phase transformer with surge diverters.

It is interesting to speculate whether any further advantage could be gained by the use of surge diverters. For instance, is it permissible to impulse-test the transformer with full-wave voltage shots only? In other words, can the surge diverters be installed so as to avoid the possibility of flashover to earth in the station apparatus between the diverters and the transformer? If this condition is fulfilled, chopped-wave impulse testing can be omitted, with a further saving in the weight of the transformer.

I should now like to make some observations on impulse testing. The possibility of detecting winding failures during chopped-wave tests by neutral-current records was first disclosed by Mr. G. H. Hickling in 1952, and, since then, a number of laboratories have been using the comparison technique for the assessment of chopped-wave tests. The triggered gap is a refinement, but not a necessity.

The sensitivity of fault-detection methods has improved during the last few years and minor disturbances of all kinds are now faithfully recorded on the current oscillographs. I should like the author's comments on this very real problem which is confronting transformer test engineers, together with some indication of the acceptance criterion he would adopt.

The main difficulty experienced with modern impulse generators is the shortening of the tail of the test wave arising from low-inductance windings—usually the l.v. windings of e.h.v. generator transformers. Equivalent circuits representing the surge loading of turbo-alternators can be assessed quite accurately. I am convinced that sufficient information is now available to devise a standard test for generator transformers, whereby only the high-voltage winding is impulse-tested and the low-voltage winding, suitably loaded, is stressed by the transferred impulse voltage.

The author's proposals for the future revision of test procedure merit examination, but it would have been better if he had expanded his ideas and given detailed reasons for his proposals.

I agree that impulse tests are quite searching, and for this reason there has always been the inclination at least to pay lip service to the idea that eventually the impulse test should be a routine one. However, I am extremely doubtful whether it can be simplified and streamlined in such a way as to allow its application as a routine test tool in modern transformer factories. The most reasonable solution is to use the impulse test as an approval test for new designs and thereafter as a sampling test on the lines already established by the Central Electricity Generating Board and described in Section 6.2.

Mr. E. T. Norris: In the orthodox principle of application of protective rod-gaps (as explained in Section 5.1) the gap length is reduced until interruptions due to switching surges and other causes are excessive. For example, the gap length for the 132 kV Grid system has, for many years, been set at 26 in, presumably from such operating experience. This orthodox principle is simple and logical, but is completely upset by Table 6, which shows that, in fact, four rod-gap operations due to surges have been swamped by 57 due to surges or other causes. Therefore, if the 26 in were reduced so that rod-gap interruptions were doubled, the total number would be increased less than 10% nominally, and, in fact, probably not at all, since the extra rod-gap operations would replace some of the 57

others. Further, the figures in col. 3 of Table 6 are interruptions rather than operations, and thus cannot do justice to the rod-gap as a protective device, since it cannot be credited with the times it operates perfectly, i.e. when it discharges the surge without causing an interruption to the supply.

The over-voltage test was originally devised as an attempt (albeit a poor one) to simulate internal stress due to surges. The development of standard surge tests has given rise to a natural suggestion, discussed in Sections 3.2 and 6.3, that the over-voltage test can be reduced or eliminated, since the power-frequency voltage distribution is uniform.

Modern improvements in surge strength, whether by electrostatic shielding, interleaving, multi-layer or multi-concentric construction, have greatly increased the surge strength, but largely at the expense of the 50 c/s stress, so that much of the margin hitherto existing between surge and 50 c/s stress has been absorbed.

Thus, whilst the voltage per turn is constant throughout the winding, the voltage between physically adjacent turns is far from uniform, and differs from it by 10 or 20 times in a modern transformer.

The over-voltage test thus assumes a new importance, which must be considered carefully before making any changes.

Mr. R. R. Pattinson: The system planner's job is no sinecure. Should he choose the wrong insulation level, he could either spend money unnecessarily or run his undertaking into serious embarrassment owing to excessive outages.

In Europe and the United Kingdom, large numbers of transformers have been operating quite satisfactorily for many years without having been impulse-tested, and the need for impulse testing is not as clear cut as in countries with high isoceraunic levels, such as Brazil, South Africa, India and Australia. A fair case can be made for impulse testing of a routine nature rather than type, but I doubt whether existing works test areas could handle the throughput.

I urge that consideration be given to developing a transferred surge test. There are many applications of 3-winding transformers where one of the windings may run unloaded, e.g. two generators connected to a step-up transformer, having separate low-voltage windings and a common high-voltage winding, and switched so that one of the generators can be disconnected leaving the other on load. In such cases, serious internal over-voltages can be generated by surges transferred from the h.v. winding, and works tests have shown how significant these are.

As system voltages rise, switching over-voltages tend to become as significant as those produced by lightning. I therefore support the author's view on works tests to simulate them. Much information exists about switching over-voltages, but little on their effect on insulation. Early agreement on the test wave-shape is essential and on the means to produce it. Perhaps a generator similar to that developed by Dr. Wilkinson* might meet the requirements.

A problem to be faced is how to test a large transformer which has had to be constructed on site. To subject it to the usual power-frequency and impulse tests seems impracticable economically, and consideration might be given to non-destructive tests in the form of a corona or discharge test, provided that works tests to prove the design have been carried out.

Mr. D. H. Ryder: Section 6.3 indicates the way towards revision of the specified insulation tests for transformers.

For procedure (*b*) of Section 6.3 we need to consider the apparatus for producing surges and also the means of detection of breakdown. No thermal breakdown is involved in switching surge tests, single surge voltage waves are preferred, and detection of failure is of the greatest importance. From these considerations it may eventually be accepted that routine impulse tests adequately prove transformers in respect of switching surges.

Procedure (*a*) is quite feasible, and, in fact, many oversea customers have requested such tests on all their transformers. But, in considering routine impulse tests we should first compare Tables 5 and 7. Table 5 indicates a failure rate of 0·25 per 100 transformers per year. The transformers which failed were not of modern design. Table 7 shows 13·5 winding faults per 100 transformers subjected to impulse tests. The indication is that the impulse test, as at present specified, is much more onerous than service conditions. It is probable that, in service, we are not encountering the short time lags illustrated in Fig. 6 of the paper. Taking this evidence into account, I submit that routine impulse tests on transformers should be made with full waves only and that chopped waves be used only on type tests. This simplified procedure would apply only for transformers operated in this country, where the lightning statistics are well known. Detection of failure on such routine test would offer no problems.

The author infers that the use of chopped waves of 115% of the basic insulation level during type tests effectively raises the tested impulse level of the transformer by 10%. This is not correct, since chopped waves are primarily intended to prove the winding capable of withstanding rapid changes of impulse voltage. They give rise to none of the voltage oscillations in the body of the winding, such as are obtained on full waves, if the initial distribution is distorted from linearity.

Mr. A. J. Gibbons: I will confine my remarks to the author's proposals for reassessment of the normal high-voltage tests applied to transformers.

The designer disposes his insulation in relation to the impulse test for which the transformer is designed. It therefore seems appropriate that the impulse test should be a routine one. When the C.E.G.B. changed from a type test to a sampling test, a number of cases of failure owing to defective material and workmanship were found. I have been seriously concerned as to the distinct probability of similar defects existing in those transformers that were not taken into the sampling scheme.

There have been a few cases of failure in service on relatively new transformers, although in most cases the damage was such as to destroy all evidence of the cause.

All manufacturers nowadays have their own impulse generator, and there should be no problem in carrying out a routine test, although I entirely agree with the author that, if this is done, reassessment of the costs involved is very long overdue.

Fault detection on impulse test is fairly satisfactory, but it has become very clear that, if there is the slightest discrepancy on a trace, the reason must be found.

Similarly, the number of failures which have occurred has reinforced the view that, in order to make satisfactory high-voltage transformers, a very high standard of cleanliness and tidiness in the shops is essential. Dirt, dust and general factory detritus scattered around on a high-voltage winding under construction is just asking for failure at a later date.

The power-frequency test, which is highly traditional and unscientific, is, in its present form and with its present assigned values, virtually finished. I should not like to dispense with it altogether, but we should examine it carefully and decide what value and duration is required as a supplement to the impulse test.

I am not so sure about the author's proposed switching over-voltage test. In the impulse test we are dealing with micro-seconds and megacycles per second, while in the power-frequency test, we are dealing with seconds and cycles per second. Somewhere between we have the kilocycle-per-second switching over-voltage. If the impulse test and the power-frequency test values

* *The Engineer*, 27th May, 1955.

are chosen appropriately, switching over-voltages should be automatically correct.

In one or two cases switching over-voltages have been transferred from the high-voltage to the low-voltage winding and have caused breakdown owing to the lower-voltage main leads being placed closer together than necessary. I do not therefore think that the case for the switching over-voltage test has been made, while the author gives no indication of how it is going to be carried out. I am sure he would not wish manufacturers to install expensive equipment until the need is entirely agreed by all interests concerned.

Mr. H. W. Hardern: I should like to endorse the author's remarks about testing a tap-changer together with the transformer. One relevant point is that many tap-changers are now provided with non-linear resistors shunted across the tappings, and only when the tap-changer and transformer are combined can true results be obtained. After all, the user is interested in the combination of the two, and so testing both together is quite logical.

A switching-surge test certainly merits examination, but the trouble is, of course, the equipment required and to decide which of the great diversity of waves that may be encountered is to be used for the test. Quite a body of opinion states that, if a transformer withstands the present prescribed power-frequency and impulse test, it will be adequate for most or all switching surges, except perhaps those produced by a very badly designed switch. There may be a case for studying switch design just as much as for a test on the transformers.

I am intrigued by the suggestion for a change in the power-frequency test. A reduction in voltage, coupled with a longer duration, may very largely cancel out. I wonder what the author has in mind in suggesting a 1 min test. It certainly gives a better chance for incipient faults to show up.

In all questions of increasing the amount of testing we must remember that we are trying to prove that a transformer is going to be suitable for 20 years' service, and not just the maintenance period. We must be quite sure that what we do in the way of increased testing will be correct.

Mr. J. L. Egginton: Section 5.1 gives the conditions in which rod-gaps are acceptable.

First, the system must withstand the loss of a circuit following a gap flashover. It is stated in the paper than an annual average of four rod-gap flashovers occurred in a period of ten years. As there are approximately 500 132 kV transformers with rod-gaps on the system, the interruptions are 0·8 per 100 transformers per year. Rod-gap flashover causes negligible damage and the transformer can be switched in immediately.

If surge diverters were fitted, we might expect a rate of 0·6 failures per 100 diverters. These might leave the fault on the circuit and would require an outage while the diverter was replaced, which costs money.

The protection given by rod-gaps has resulted in 20 transformers breaking down in ten years, during which 55 major breakdowns occurred on tap-changers. Winding failures at present do not need the first attention.

The only justification for surge diverters is to reduce the cost of transformers, as shown in Fig. 5.

I agree that, with 132 kV transformers and 275 kV auto-transformers, the slight extra cost justifies the greater reliability obtained by omitting surge diverters. We should not be justified in reducing the impulse strength of 275 kV double-wound transformers without previous experience with surge diverters, and the initial costs of such installations would be high. Even if successful, the decision whether to accept the lower standard of security would remain.

Section 5.3 describes the conditions under which surge diverters are installed on the Grid system. This does not take into account the theory that the impact of the surge is divided by the number of parallel lines connected. Can the author state whether this theory is substantiated in practice?

Is the reason for installing surge diverters on wood-pole lines that such lines are nearly always transformer feeders and there is no reduction due to parallel circuits, or is it due to the higher impulse strength of such lines? The slope of the wavefront is steeper, and although the rod-gap will limit the maximum, the rapid rise may cause conditions where curve (*c*) drops below curve (*a*) in Fig. 6.

To install a surge diverter on a generator transformer will probably increase the total outage time. At a generating station there are normally at least four circuits connected. Therefore the reduction of the surge at the terminals of the transformer could be significant.

Dr. J. R. Mortlock: Essentially the basic insulation level is obtained by accepting surge-diverter characteristics and multiplying them by 1·25 to obtain a sufficient apparatus life. The cost of the diverters is usually negligible compared with that of the transformers and switchgear, and yet they dictate the major cost. However, some consideration must also be given to switching surges.

From Table 3 the switching over-voltage factors for 132 and 275 kV are approximately 4 and 3·75. Multiplying by 0·8, in order to obtain sufficient apparatus life, acceptable factors would be 3·2 and 3, respectively. With modern switchgear designs a factor of 2·5 is usual; with future designs the factor may possibly be 2·3.

Accepting 2·5 and multiplying by 1·25 for life and 1·25, as given by the author, for correlation with the full-wave impulse test level, on a switching-surge basis, basic insulation levels of 422 and 880 kV would be acceptable for 132 and 275 kV, respectively, compared with the present 550 and 1 050 kV. The corresponding diverter maximum voltages would have to be 338 kV (422 × 0·8) for 132 kV and 702 kV for 275 kV. This is a challenge to the designers of diverters, since, even if they cost twice as much as the extant models, the overall saving would be appreciable.

Admittedly, lightning would remain a problem at the lower voltages, but, for 600–700 kV systems, the criterion is switching surges and it is essential that basic insulation levels should not be dictated by the limitations of surge diverters.

Mr. E. Tobin: When protection is by rod-gap only, the minimum insulation level for transformers is dependent on the lowest gap setting that can be tolerated.

The author states that he is using 26 in for 132 kV and 48 in for 275 kV systems. The sparkover values of these gaps are approximately 500 and 860 kV, respectively, giving protection at 90% of the impulse level of 132 kV transformers and 82% of the impulse level of 275 kV transformers.

Service experience on 132 kV indicates that satisfactory operation is obtained, and therefore a 90% protective level may also be satisfactory for the 275 kV system. If a protective gap setting of 45 in can be tolerated, the insulation level of the 275 kV transformers could be reduced one step from 1 050 to 900 kV.

Reducing the insulation by one step would mean a reduced impulse test and power-frequency voltage test to earth, but I recommend that the test between phases might be based on the 132 kV system experience. The power-frequency test between phases of 132 kV transformers has been about 1·6 times the system highest voltage, and this test appears to be adequate to ensure freedom from trouble owing to switching over-voltages.

For 275 kV transformers the power-frequency test between phases might therefore be about 480 kV, even though the power-frequency test from line to earth is reduced to 390 kV.

Mr. E. L. White: One accepted method of making the power-frequency test on a 3-phase transformer having partially-graded insulation is to induce two-thirds of the test voltage between line and neutral and one-third between neutral and earth. If the voltage per turn attained in this test is induced under service conditions, the line–earth voltage is only two-thirds of the test voltage, since the neutral is then solidly earthed. It follows that, in respect of the inter-turn insulation, the switching-surge strength deduced in col. 4 of Table 3 is overestimated by 50% if this test method is used.

In the impulse test the inter-phase voltage can be limited to the peak voltage of the applied wave, whereas, when a switching surge occurs, the inter-phase voltage is likely to be about 150% of the line–earth voltage. Thus, in relation to the inter-phase insulation, the figures in col. 3 of Table 3 are overestimated by about 50%. For similar reasons the switching-surge strength of the inter-phase insulation deduced from the power-frequency stresses under test conditions falls considerably short of the estimate in col. 4.

I hope that these remarks will not be construed as implying inadequate insulation strength in any transformer tested according to recognized methods, but that they will draw attention to the anomalies which result from having alternative test methods, as well as to the shortcomings of Table 3.

For future procedure I should like to see established a switching-surge test in which the voltage distribution between the various parts of the insulation corresponds to that likely to occur in switching surges under service conditions. Coupled with satisfactory fault-detection techniques, this could be a routine test, eliminating the need for a power-frequency overvoltage test and leaving the impulse test as a type test.

Mr. F. W. Gee: In the Introduction the author has been forced to adopt a definition in which he states that the insulation level of a transformer can be defined in terms of the voltage tests for which it is designed. It is all that is available, but a true level would be 99% of the actual breakdown strength of the transformer. This is a figure on which he would have great difficulty even in collecting opinions, let alone facts. It is an insurmountable difficulty, because the only way to get them is to carry out a routine test to destruction, which does not lead to great output. It is the comparisons on this artificial basis which account for the commendable caution in drawing conclusions.

The difficulties are enhanced if we consider Table 5 giving type-test experience and Table 7 giving operating experience. One way of linking the two would be to make comparisons of the two figures, but operating experience on the ones for which he has quoted type-test experience can be expected in about 15 years' time. If we want to make any changes, we want to make them before that, and so there would have to be some guesswork.

When we consider operating experience, the number of breakdowns is so small that it is unsafe to draw any detailed conclusions. The only definite conclusions are that the transformers are strong compared with their operating conditions.

Mr. Pattinson's point about 3-winding transformers and the voltages which can arise in service raises another point which will remain true however carefully a specification is compiled. It is nearly always possible, and would sometimes be easy, to design a transformer that would pass the test but fail in service. However, a manufacturer who tried to shelter behind a specification in that manner would not survive very long, and it is the desire of the manufacturer to find any weak spot in the transformer before it goes into service. This is the user's biggest safeguard, when combined with a reasonable specification.

The author states that 'Some 250 transformers are now 20 years old and fault incidence is likely to increase.' However, there is another factor. By adding new transformers the average age on the system is kept down.

Mr. M. P. Reece: I should like to put forward a method which might be used for surge tests on transformers.

Small sealed-off vacuum switches with tungsten contacts are now available, and when these are arranged to have a high contact-separation velocity, they act as very effective current choppers.

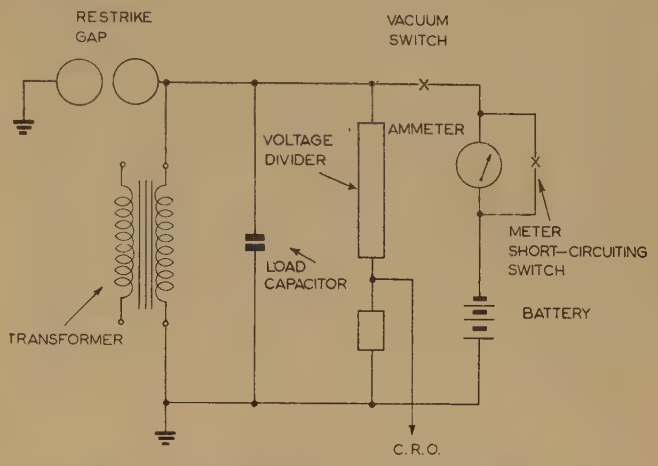


Fig. A.—Switching-surge test circuit for transformer.

We have made some tests in which the circuit of Fig. A was used to induce 30 kV in the 11 kV winding of a 11/6·6 kV 3·7 MVA transformer, by chopping a current of 10 amp d.c. with a small vacuum switch, some 6 in long and 2 in diameter. The direct current was established by three 2-volt lead-acid cells in series. The spark-gap was arranged to flash over at 30 kV, to simulate the effect of a restrike. Two representative oscillograms are shown in Fig. B. The very large damping of the

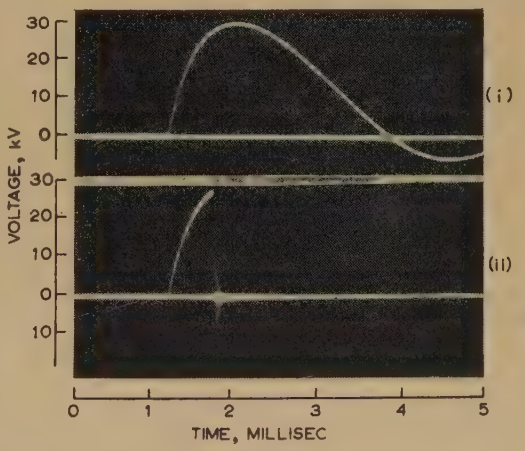


Fig. B.—Switching-surge test on 11 kV transformer: current chopped at 10 amp.
(i) No restrike.
(ii) Simulated restrike.

circuit is due to high iron losses in the very old transformer used.

The switch is rated at 60 kV, so that a series connection of a reasonable number of switches should be capable of inducing full-scale test voltages. The waveform produced in this way has the two fundamental attributes of a switching surge, namely

a high voltage applied for a relatively long time followed by a sudden step.

If it were necessary for the voltage to reverse during the step, the side of the spark-gap shown earthed in the Figure could be connected to the line terminal of a capacitor initially charged to a suitable voltage of opposite polarity.

No experiments have been made to investigate fault detection, but it seems likely that the techniques used in impulse testing could be applied.

Mr. D. M. Cherry: The paper discusses the possibility of reducing transformer insulation levels, but the economic advantages of doing so are not reliably known, judging from the differences in the cost curves which the author has given. A valuable complement to the paper would be another by a transformer designer, discussing the effect on transformer construction and cost of specifying differing insulation levels and methods of tests.

When one considers the possibility of reducing insulation levels, it is as well to consider Table 7. With the worst interpretation, in the first three years recorded, one can deduce that 40% of all the transformers installed would not be able to meet the specified level. Therefore, in effect, the C.E.G.B. are already conducting a full-scale experiment in reduced insulation levels, not only with their pre-war transformers, but also with many of their post-war units. Unfortunately, because the insulation level of those which are sub-standard is not known, the statistics of failure will not give conclusive evidence.

Modern switchgear can be designed to give switching surges of a low value, and even with those types of circuit-breaker which can produce severe surges the level can be effectively controlled by surge diverters. The switching-surge aspect can therefore be overemphasized, and I suggest that attention should rather be concentrated on the other test proposals put forward by the author.

Mr. W. Casson: Experience in this country in the past with high-voltage surge diverters has not been very satisfactory, mainly owing to their inability to withstand the unbalanced voltage gradients created by pollution. New designs of surge arrester should give improved performance, but we do not yet have enough of them installed. It would be at least ten years before we could obtain full service experience, and I do not think we should wait this long before deciding to employ, on a limited scale, designs of transformers with lower insulation levels. The problem of protecting them whilst getting the necessary experience on surge diverters could be overcome by adopting the following method.

This consists in providing rod-gaps on each phase at a convenient point on the busbars outside the zone of the transformer protection. These rod-gaps would not be connected directly to earth but through a circuit-breaker and resistance. The circuit-breaker would normally be closed, and in the event of a gap flashover, a relay would be arranged to operate instantly and trip the circuit-breaker, but the transformer would not be tripped out. After a short time the circuit-breaker would be automatically reclosed ready for a further operation. Back-up co-ordination gaps would also be provided on the transformer, but these would be set to operate at a higher voltage than the special gaps, which could be set to a much lower value relative to the insulation level of the transformer than has been the practice in the past.

With such an arrangement it should be possible to obtain important basic data regarding over-voltages due to lightning and other cases, and full recording of the operations could easily be effected.

The policy of reducing insulation levels on transformers when protected by surge diverters has been successfully exploited in the United States, and I do not see why it should not be done here, although Fig. 4 seems to indicate that the gain in reduced cost of transformers is much greater in the United States than it would be in this country.

Mr. D. J. Miller: It is dangerous to make a too ready generalization about the effect of surge diverters on system fault performance.

We have had occasion to compare the characteristics of surge diverters drawn from a wide field of manufacturers both in this country and abroad. It is apparent that their design is far from stabilized. Even in this country the characteristics vary widely, and the differences are even more marked when they are of foreign manufacture.

The author draws his conclusions from References 25 and 26, both of which are Continental. We have had occasion to use in the tropics surge diverters of foreign manufacture which were not hermetically sealed. Whether from this cause or not, the performance was unacceptable. Subsequently we changed to other surge diverters which were hermetically sealed and had improved electrical characteristics. Using these, I would say that the performance has been better than that given by the author. The author's figures are probably based on Continental surge diverters, many of which are even now not hermetically sealed.

With regard to Fig. 4, we have had occasion to obtain alternative prices for transformers of 550 and 650 kV impulse insulation level from the Continent. I think that the difference was about 9% for transformers of about 30 MVA, which is somewhat greater than that shown for the British transformers, but very much less than that for the American ones.

Mr. D. E. Singer: Whilst rod-gap protection has undoubtedly contributed to low system fault incidence, a more severe criterion i.e. impulse testing, has revealed a relatively high rate of rejection (see Table 7). This aspect, rather than service experience, encourages the inclusion of impulse testing on a routine basis, particularly when we consider the arbitrary rate of sampling adopted. However, without considerable improvements to reduce the time for test and the introduction of a detailed test code, the prospects daunt me.

With regard to the former, the testing time varies considerably. A well-disciplined staff operating on efficient production methods provides a service superior to the case where each test is treated as a research project with consequential delays. Greater attention must be devoted to this than hitherto.

With regard to a test code, techniques should now permit a more rigid procedure, particularly when we consider that 'routine' implies tests on all phases of each transformer. Hitherto, considerable discretion has been exercised in the manufacturer's favour, owing to limitations of test facilities. Many premises are ill-equipped to meet routine testing requirements. Whilst B.S. 923 covers waveshape parameters, no standard exists covering other variables, e.g. polarity, controlled chopping, voltage overswing, earthing conditions, tapping position, detection sensitivity, acceptance criteria, etc. Furthermore, divergent views are held about the form of supplementary records, which, I consider, should include fast and slow time sweeps, say 30 and 300 microsec for all voltage applications. No criteria exist for the occurrence of 'self sealing' faults, which are not always revealed during subsequent voltage applications. These several aspects require explicit guidance in test-code form preparatory to routine impulse testing.

With regard to the economics of limited reduction of insulation level, even modern design techniques necessitate considerable safety margins to cover material and manufacturing weaknesses. Any price reduction can therefore be of no more than token value, when we consider the limited drop in insulation level envisaged.

Mr. A. H. Barton (*communicated*): In Section 3(*c*) it is stated that 'For transformers directly connected to the terminals of a generator, surge diverters are provided . . .'.

Generators switched at 275 kV are of such a large capacity that they are generally connected to substations where at least four outgoing circuits are also connected. If overhead connections are made from the generator transformer to the 275 kV switchgear, these are usually run through an area where high structures and buildings provide a degree of protection from a direct lightning stroke. These connections are usually further protected by an overhead earth wire. The only surge which would therefore appear to have a reasonable chance of reaching the transformer terminals is a switching over-voltage, and this can be left to the ingenuity of the switchgear designer.

In the circumstances, and bearing in mind that 275 kV surge diverters are not only large pieces of apparatus to accommodate, but also necessitate large safety clearances, I suggest that they might be omitted from 275 kV generator transformer circuits.

Mr. W. S. Lovely (*communicated*): Our primary concern should be to achieve completely reliable transformers at a price which is satisfactory to users as well as suppliers, and we should be aware of British Standards and testing which may boost prices. Bearing in mind the good record of transformer service over the last few decades, special impulse design should be used on transformers up to, say, 15 MVA and higher voltage below, say, 100 kV only (*a*) where working conditions compel it, and (*b*) where, though working conditions do not compel it, it can be achieved at no greater cost to the buyer than a non-impulse design of proved merit and thereby can help standardization. With regard to testing, can we not have too much elaborate test plant in the country with a danger of its being over-used? A snowball scheme of testing may develop whereby tests get larger and more complicated just because the plant is available together with large numbers of enthusiastic, highly-trained and highly-inventive engineers.

I am interested in suggestions for the adoption of lower insulation levels for transformers than those proposed in the paper. Obviously the ideas would have to be proved by type tests, and, in the interests of economy, such tests might be made a 'national' or 'pooled' matter rather than involve a large number of large-scale competitive efforts.

With regard to the proposal to place impulse design on a routine basis, I feel that this must be productive of increased costs, and, as has been mentioned by other speakers, it may not be justified. I still have great faith in the old-established power-frequency tests and would not like to see these seriously altered—at least not until there is ample evidence to justify such a step.

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 23RD MARCH, 1959

Dr. L. L. Alston: I wonder whether the view expressed in Section 1, i.e. the operation of a rod-gap always results in a system fault, is not unduly pessimistic. It has been shown recently[A] that the power current must build up to about 1 amp for a power arc to become established. The power current might fail to attain that value if the surge were of short duration, particularly if the surge occurred well away from the peak of the 50 c/s voltage wave. In the absence of special measurements, flashovers which do not cause a fault may escape detection, and it would be interesting to know whether any attempt has been made to record them.

The author comments in Section 6.1.1 on the difficulties associated with the detection of chopped-wave failures, but he does not mention the technique of energizing the transformer at power frequency during impulse tests. This technique was used at one time in the United States and Sweden, and its object was to produce a power arc when impulse breakdown occurred; the detection and location of the breakdown were then relatively simple. Unfortunately, it was found that a power arc did not always occur, and the technique was abandoned. However, recent work[B, C] has indicated that a power arc is initiated provided that a current of about 1 amp flows in the winding under test when flashover occurs, and it would be worth while to reconsider this technique, both for full-wave and chopped-wave impulse tests.

Mr. R. W. Flux: The recorded number of rod-gap operations is too small to provide definite evidence on the efficacy of the protection afforded, but the ratio of transformer lightning faults to the number of gap flashovers is disappointingly high.

The peak value of the chopped wave should be higher than that of the full wave, as this relationship is representative of actual operating conditions. A chopped wave may over-swing beyond zero owing to resonance in the test circuit. These over-swings can create greatly increased inter-coil voltages. It seems important to determine whether over-swinging occurs when a rod-gap flashes over in service and to define more precisely than at present the conditions for chopped-wave testing.

Although experience would justify the adoption of routine impulse testing, practical difficulties are considerable. To retain the present procedure of testing one transformer in ten but to regard it as a sample rather than a type test seems to be a reasonable compromise.

Mr. G. H. Hickling: Surge diverters are referred to in the paper as being 'fundamentally less reliable' than rod-gaps, and whilst the former have certain admitted advantages in relation to the possibility of reducing insulation levels, it is shown that, in general, the rod-gap characteristic is such as to afford satisfactory protection to the transformer. The practicable rod-gap setting depends upon the frequency of flashovers, and the evidence in Table 6 that an average of only four out of 57 outages were due to this cause shows that the present protective level is not obtained at the expense of continuity of supply. We may therefore conclude that rod-gap protection is likely to remain, and with it the need for chopped-wave testing.

It is stated that the present 115% chopped-wave test results in an increase in the overall insulation margin (as compared with full-wave testing alone) of about 10%; but it should be remembered that, so far as the transformer inter-coil insulation is concerned, the chopping of a wave produces stresses of much greater severity than that applicable to a full wave. Whilst there would be definite advantages in reducing the chopped wave to the 100% test level—particularly in expediting the test procedure—it is clearly a matter for specification whether this shall be done. It is not specifically related to controlled chopping methods. I also agree with Mr. Flux that a more rigid specification of the chopped-wave characteristics is desirable in order to obtain some consistency in the severity of the test.

In his Conclusions the author makes proposals for revised testing methods which include the adoption of the impulse test as a routine test. However, before this policy can be contemplated by manufacturers, it is essential that a more satisfactory criterion be agreed on for accepting impulse test results as satisfactory. Oscillographic recording techniques have become progressively more sensitive to minor disturbances, irrelevant to the impulse breakdown strength of the winding, which give a distinctive type of indication clearly distinguishable from break-

down of the winding insulation proper. The author's comments would be appreciated on the recognition and acceptance of such disturbances when assessing the result of a transformer impulse test.

With reference to Section 6.2, what type of fault is classified as a 'processing' fault, and how are these identified?

In connection with the final paragraph of Section 6.1.1, my own experience has been that, in practically no circumstances, has it been necessary to resort to relaxation of waveform tolerances due to inductive or capacitive loading by the transformer. It is very satisfactory that only two transformers manufactured since 1939 have failed owing to lightning faults in service. Evidently the policy of impulse type-testing is giving satisfactory results.

Mr. S. Zoledziowski: I should like to discuss the drawbacks of the power-frequency voltage-withstand test as a method of testing the insulation of transformers. First, if corona is present during the test, it may produce partial breakdowns, thus shortening the life of the insulation. Secondly the test may not detect the presence of moisture, and it gives no indication of the corona inception voltage. The time has come to consider modification of the standard power-frequency test, which should aim at decreasing the danger of insulation damage and making the test more searching. A power-frequency test at reduced voltage, as suggested by the author, would tend to decrease the danger of insulation damage. However, other measurements would have to be introduced to detect moisture and corona. Methods of measuring the moisture content of oil-impregnated paper insulation have been developed, and, in many countries, transformers must satisfy certain requirements before they are energized.[D,E] Methods of measuring corona have also been developed,[F] but corona levels which can be permitted have not been yet established for transformers. It is too early to introduce generally valid requirements into British Standards, but I feel that, to indicate the importance of these tests, they should be mentioned in the same way as impulse tests were in B.S. 171: 1936.

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THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. G. B. Harper (*in reply*): To take maximum advantage of available space my reply is given on a subject basis rather than by individual answers to all questions in the order raised.

Mr. Rippon and a number of other speakers have commented on the problem of introducing routine impulse voltage tests. Reference to this matter in the paper is coupled with suggestions for complete revision of present test procedure, but, considering the value of the impulse test as indicated in Section 6.2, I believe its eventual adoption on a routine basis, at some future date, to be inevitable. As stated by Mr. Gibbons all transformer manufacturers now have facilities for the test, and experience with the use of this equipment has shown general improvements in techniques over the last few years. Procedure delays are, to a great extent, conditioned by the attitude adopted towards the test, and I endorse Mr. Singer's views in this respect. A realistic approach as a works production test considerably reduces the time involved and usually produces superior records. As suggested by Messrs. Flux and Singer, however, there is a definite need for more precise definition of requirements to take account of the special aspects for tests on transformers.

Reference is made by Messrs. Rippon and Hickling to the interpretation of minor disturbances on impulse test records, disturbances not necessarily indicative of winding failure. A criterion that has been proposed for such cases is repetition of voltage applications, no increase in the disturbance being taken as proof that the cause is other then insulation failure. Whilst this may be acceptable for marginal cases, as the whole basis of fault detection is by comparison, acceptable divergence is a question of degree and, in my opinion, can only be decided on the basis of experience for the particular circumstances in question.

In reply to Mr. Hickling, the faults recorded in Table 7 attributed to inadequate processing were identified by careful examination of the damage resulting from the test, processing being defined as drying out and vacuum treatment.

The inference of the comparison made by Mr. Ryder between Tables 5 and 7 is, I would suggest, misleading, and this view is to some extent substantiated by the remarks of Mr. Gee. In principle, tests should show a reasonable margin over anticipated service conditions, and therefore must be more onerous. Direct comparison between the two Tables is not valid, and, as stated by Mr. Cherry, the units which failed on test can be considered as sub-standard with respect to specified requirements.

Mr. Ryder suggests routine impulse tests could be limited to full waves with chopped waves retained as a type test. Usually the time taken for application of the chopped waves is small relative to that of the complete test, but, if any real economies could be shown, such a step would have certain advantages over the present sampling basis. I would prefer, however, to use the chopped waves on a sampling basis rather than strictly as a type test.

I fully support the views of Messrs. Rippon and Pattinson with regard to tests by transferred surge for cases where stresses on the windings, in service, are confined to this form of overvoltage. Such a procedure, correctly representing both amplitude and form, has obvious advantages over selection of an arbitrary test level.

A number of speakers refer to proposals relating to the possible introduction of a test corresponding to switching overvoltages. These proposals were included, not with the intention of complicating test procedure, but with the object of suggesting a more logical test sequence. Further investigation may prove that, in conjunction with the impulse test, a short-duration or momentary power-frequency test is adequate for this purpose. An additional test cannot be justified on the basis of service experience, and its introduction is valid only if it shows advantages in other respects. The form of test described by Mr. Reece could be of use for general investigation.

Mr. Norris draws attention to the influence of methods adopted for improvement of surge strength on 50 c/s stress.

Reconsideration of test procedure must take account of these circumstances, but any form of induced test naturally compensates for increased inter-turn stress resulting from winding transposition. The variation in voltages developed for different test connections and their effect on transformer insulation strength referred to by Mr. White is a further anomaly resulting from present procedure which could be improved by re-assessment of existing requirements.

On the question of reduced insulation relative to the use of surge diverters, I agree with Mr. Egginton that, for present circumstances, the marginal extra cost of transformer insulation justifies the greater reliability obtained. This position, however, needs to be kept under review and full account taken of any manufacturing improvements in relevant equipment. Although based on deductions made from satisfactory protective levels in the case of the 132 kV system, further operating experience with the 275 kV system is desirable before the measures proposed by Mr. Tobin are contemplated. In reply to Messrs. Egginton and Barton, the conditions described in Section 5.3 refer to general principles, and, in practice, there are obvious advantages in the examination of individual cases. The theory of reduction in surge voltage by parallel circuits is to some extent substantiated by the comparison given in Table 6. Mr. Norris and Dr. Alston, however, rightly draw attention to the fact that rod-gap flashover need not always result in power follow current, and therefore the interruptions recorded in Table 7 are not necessarily a true indication of the total number of gap operations.

With regard to the comments made by Mr. Miller, References 25 and 26 were chosen particularly as representing reliable data based on extensive service experience with the use of modern surge diverters, for the very reason that it is dangerous to generalize on these matters. As pointed out by Mr. Casson, service experience with surge diverters in this county leaves much to be desired, and figures for performance in Great Britain were not included in the paper partly on this account and partly because their very limited use does not permit a fair comparison.

The introduction of some form of corona or discharge test for transformer insulation mentioned by Messrs. Pattinson and Zoledziowski would provide a useful complement to dielectric tests in general. Many problems remain to be solved, however, before a simple and reliable procedure suitable for routine testing is devised, although the undoubted value of such a test merits serious attention.

DISCUSSION ON 'OPERATIONAL EXPERIENCE AT CALDER HALL'*

Before the North-Eastern Centre *at* Newcastle upon Tyne 27*th October*, *the* North Midland Centre *at* Leeds 2*nd December*, 1958, *the* North Staffordshire Sub-Centre *at* Stoke-on-Trent 16*th January*, *and the* North-Western Supply Group *at* Manchester, 23*rd February*, 1959.

Mr. P. Knowles (*at Newcastle upon Tyne*): The Calder Hall plant clearly behaved very largely as the designers expected, but it can be seen that, as soon as the plant had been initially assessed, the process of seeking more output and more information from it started. Assessment of the state of the reactor core and its rearrangement to improve output is continuous and rewarding work, and new facts are continually emerging. It is because the ways of getting the best out of the plant require continuous work, and because it is clear there are still very many aspects to be understood and new facts to be discovered, that the inside of the security fence at Calder Hall should still be a much better school than the one established outside it: it is the only real source of practical knowledge on power reactors in this country to-day. It is to be hoped that the Windscale and Calder Hall turbine incidents will soon be seen by the U.K.A.E.A. in true perspective, and will not deter them from their continued inquiry into the behaviour of the Calder Hall reactors, which is so important to our civil nuclear programme.

It is clear that Calder Hall has confirmed the gas-cooled graphite-moderated reactor as a suitable vehicle for the start of the civil programme. Such additional facts as the existence of the overall positive temperature coefficient means that the claim for inherent stability has to be abandoned, but it does not perceptibly alter the 'feel' of the reactor or make its control more difficult. It will, of course, mean that xenon instability effects, which are not noticeable at Calder Hall, will become very important in the larger high-flux civil reactors, but this is small cause for concern, for designers have no doubt already produced more-complex control systems to take care of such effects. Moreover, by the nature of its principal product, Calder Hall cannot confirm the 3 000 MWD/tonne target figure for fuel irradiation on which the economy of civil stations rests so very heavily, but at least it has confirmed that, if this target is not reached, loss of reactivity will not be the cause.

Mr. E. J. M. Marrian (*at Newcastle upon Tyne*): In Section 4.2 the author mentions that unscheduled trips of the reactor have occurred through defective components and maloperation during maintenance. It is understandable that emphasis should have been placed on ensuring that a faulty reactor is shut down as soon as possible, but is it not just as desirable to prevent a healthy reactor being shut down unnecessarily? First, therefore, the safety circuit should be above reproach, as to both the integrity of the various components which comprise the tripping chain and the way in which they are connected. For instance, it would be better if the supplies used for the safety circuit were earthed, not solidly, but in such a manner that one stray earth occurring elsewhere in the circuit could be made to initiate an alarm without either causing or preventing a shut-down. Secondly, for ease of maintenance, every instrument, relay, fuse, plug and socket, cable connecting block, etc., which, when disturbed, can cause the reactor to shut down, should be made easily recognizable, possibly by being painted or otherwise marked in some distinctive colour. The various groups of non-tripping alarms should also receive the most careful attention, since a maloperation can confuse the operator and may possibly lead eventually, if not to a dangerous situation, at least to an unnecessary fall in output. It would be most interesting to know whether the many thermocouples employed, particularly those no longer accessible, are giving useful service. Have there been any failures? If so, does the author consider that any improvement should be sought either in their design or in the manner in which they are installed?

Mr. A. R. Rumfitt (*at Leeds*): When describing the operational experience with particular reference to the reactor section the author focuses attention on the problems arising with the handling of the control rods and refers to the methods of dealing with all associated parts after the reactor has become active. No reference is made, however, to the problems which must ultimately arise in dealing with the graphite moderator. On the assumption that the limit of the useful life of a reactor will be the period for which the graphite moderator remains efficient, what action will have to be taken with this component when the reactor must be

* Stretch, K. L.: Paper No. 2594 S, April, 1958 (see 105 A, p. 475).

closed down? With conventional power stations there is no reason why an old site cannot be re-used to accommodate the latest types of generating equipment. With an atomic station, however, using reactors of the type described in the paper, it can be envisaged that, at final shut-down, all the apparatus contained within the biological shield will have to be sealed off to prevent contamination arising from the high degree of radioactivity within this shield. Must we therefore look to a future in which the countryside is littered with extinct reactors, which, in turn, will prohibit the use of the surrounding area for an incalculable number of years?

Mr. V. J. Vickers (*at Stoke on Trent*): Mention is made of the leakage of oil from the blower-shaft seals into the reactor circuit as the result of maloperation of a valve. In my experience, this sort of thing can always happen, no matter how precisely the operating procedure may be laid down. It has been experienced with hydrogen-cooled turbo-generators, where we have to seal the shaft against leakage of hydrogen. Normally, extreme cleanliness is not so vitally important in such machines as it is in a reactor, and the simplicity of an oil seal is considered to outweigh any risk of oil gaining access to the interior. The author states that the oil detraining system has been modified, but even if these changes can be regarded as sufficient safeguard against a repetition of the trouble, I still question whether the small amount of oil vapour can be adequately controlled in order to eliminate contamination over a long period. Has any consideration been given to the possibility of devising some form of seal which does not have to rely on oil as the sealing medium?

The relatively high solubility rate of carbon dioxide in oil, which even at atmospheric pressure is some 12 times that of hydrogen, must present a problem: but without a knowledge of the principle of operation of the seal-oil system it is impossible to assess just how important it is. I conclude, however, that it is of significance, because oils with reduced gas solubility and low vapour pressure are now coming onto the market. Have such oils exhibited any undesirable characteristics, because they may be of assistance in reducing the rate of gas usage of hydrogen-cooled generators, which begins to be of significance as the operating pressures are raised?

A considerable length of relatively large gas ducting is involved in the Calder Hall installation, and I should be interested to know what form of gas sealing has been adopted at the various joints, and also what method of leakage detection was employed, during both initial proving and normal operation.

Mr. J. L. Ashworth (*at Manchester*): The supply industry has a vital interest in the successful economic operation of nuclear power stations. The annual rate of increase of energy demand exceeds the rate of increase in coal production, and some alternative to home-produced coal is needed to fill the gap. Imported oil is being used at present, but it cannot be regarded as a stable factor in our future economy, and the obvious and practical alternative is nuclear energy.

The C.E.G.B. are building a number of nuclear power stations; the first two, to be commissioned in 1961, have output capacities of 275–300 MW, but other stations will have much larger capacities, in order to reduce capital expenditure per kilowatt by using large plant items. For example, a coal-fired station using 550 MW turbo-alternators is estimated to cost under £40 per kilowatt, compared with £78–£80 per kilowatt using 30 MW sets.

At the present time the capital cost of a nuclear power station is about three times that of a coal-fired station of equal capacity, so that for reasons of economy the nuclear stations must be operated at as high a load factor as possible; but even so it is very comforting to have the author's assurance that the Calder Hall reactors have been found to be so flexible that load changes between 15% and full load can be effected extremely easily and quickly. This feature will facilitate maintenance and operation.

In Section 3.3 the authors state . . . 'Immediate indication of a burst not only prevents activity being recirculated and spread round the circuit, but also enables the circuit to be kept at an extremely low degree of contamination'. I do not know how quickly from the time the first indication is given that the particular channel in which the burst cartridge lies can be detected and the cartridge removed, but I should have thought that the time interval would have been quite sufficient for the gas to circulate radioactive particles all round the system. I recently had an experience with a damaged radioactive capsule. The size of the capsule, in comparison with the fuel cartridge at Calder Hall, is minute, but a considerable amount of work was carried out to bring the contamination from the damaged capsule in a building to acceptable limits. I appreciate that the contamination in the reactor is under dry conditions and it is therefore a question of removing dust, but I should not have thought it possible to remove all the dust and therefore there must be some residual radioactivity which may have accumulated in the passage of time when more cartridges burst.

Will the author enlarge on the safety aspect of people working within the gas circuit? I note in Section 6 that air lines were used when the heat-exchangers were inspected, and presume this means that the operators wore protective clothing and breathing apparatus to prevent the ingestion of dust.

Mr. J. S. Mills (*at Manchester*): The steam-raising units at Calder Hall were novel in many respects but particularly in that they were sited out of doors and that they contained radioactive gas. Since the commissioning period on some units extended into winter, what lessons were learnt concerning frost hazard? The first units at Calder Hall were subjected only to an alkali boil-out; what arrangements were necessary in respect of blowing down to maintain reasonable feed-water quality, particularly during the early months of operation, and did the presence of radiation influence the schemes?

Will the author outline briefly the 'permit to work' system used on the electrical system at Calder Hall, particularly during the working-up period covered by the paper? It would seem that the electrical supplies could be divided into three categories, namely

(*a*) Essential supplies necessary to guarantee the safety of the loaded reactor.
(*b*) Control supplies.
(*c*) Normal electrical supplies.

Only in the third case can the 'permit to work' be issued solely on the normal grounds of a conventional power station; in case (*a*) the safety officer must be consulted if the reactor is loaded; in case (*b*) the operators must have an exact knowledge of what is being done.

Mr. E. Gabriel (*at Manchester*): The question of staffing is referred to only briefly in the paper, and the fact that the Calder Hall reactors were built for production entails a different approach to the method of operation. This tended to fall into two distinct compartments, namely operation of the reactor and associated equipment and operation of the more conventional power plant, and this division was extended up to management level. The operation of the future reactors at various loads, and the probable absence of a large steam-dump capacity, makes this division increasingly difficult to maintain. What are the author's views on this division of operational responsibility in the light of his experience at Calder Hall?

The author has stressed the importance of the rigorous testing of as much plant as possible in the pre-commissioning period. It is also stated in the paper that the first recharge of No. 1 reactor was used to give the charge and discharge machines a prolonged

test. In view of the importance of the charge-discharge equipment on the gas-cooled reactor, it is surprising that no mention is made of rigorous testing of this equipment prior to fuel loading on the Calder Hall reactors.

The maintenance of clean conditions to a high degree in the manufacture, transportation and construction of reactor components is a very costly process. One wonders whether the very high standards laid down at present are really necessary, and whether at least some relaxation in these standards could be tolerated without prejudicing reactor operation.

Mr. M. W. Jervis (*at Manchester*): The view has been expressed that, being a prototype reactor, a larger number of instruments than are strictly necessary are installed at Calder Hall and that the C.E.G.B. stations would probably have less-complex instrumentation. The reverse appears to be the case, however, and it is being found necessary to fit even more instruments than were used at Calder Hall. These include complex gas-analysis equipment and quite sophisticated automatic data-loggers with computer-like facilities. It would be interesting to have the author's view on this trend from the operational aspect.

The problem of inaccessibility of many areas near the reactor has been stressed, and closed-circuit television would appear to be a very important factor in this matter. Will the author comment on the performance and utility of the Calder Hall television equipment?

The reactor control room has a mimic diagram arrangement for the grouping of the reactor instruments. Is this justified for such a simple gas circuit, and do the operators find it any improvement on a simple geometric layout?

Dr. J. Shaw (*communicated*): I should like to discuss further the question I raised at the London meeting concerning the regagging or retrimming of the neutron-flux distribution to correlate the flow and flux patterns. For the civil reactors I feel that this problem is of great importance, since the design bulk-outlet temperature must be achieved if a loss in electrical output is to be avoided. The results obtained during the commissioning and operation of reactors Nos. 1 and 2 at Calder Hall, and described in the paper, showed that, although several attempts were made to correlate the flux and flow, the channel outlet-temperature drop in the core centre was not entirely eliminated. Such conditions in the civil reactors would certainly affect the economics of the station.

In view of this, some form of adjustable gagging, although expensive, may prove extremely useful during the operation of the station. The flux need then not be shaped to such a fine degree, the final trimming being carried out by adjustment of the gags. Although appreciating that a detailed answer to this question depends upon the particular mechanical details of the reactor, I should appreciate the author's generalized comments, especially with regard to the provision of adjustable gags.

In view of the fact that the Calder Hall reactors have been operated with small positive overall temperature coefficient, I should appreciate the author's views on the necessity, if any, of changing the operational techniques during the change from operation with negative to positive coefficients.

Mr. K. L. Stretch (*in reply*): Mr. Knowles is correct in urging that, despite the progress made already and the attention drawn to the risks involved in experimental work by the Windscale and Calder Hall incidents, it is essential that development testing should continue on the Calder Hall reactors. In view of the narrow front on which the British nuclear programme is advancing, the information from wide variations in operating conditions is as essential as that which must be compiled by steady running.

While agreeing with Mr. Marrian's comments on the need for further development on instrumentation and control to avoid unnecessary shut-downs, it is fair to emphasize that the degree of reliability achieved at Calder Hall was exceptionally good for this stage. The television equipment in particular behaved nobly in view of the treatment it received. The value of mimic diagrams depends on both the complexity of the circuit and on the quality of staff, and is likely to grow as reactors start to be treated as standard operational plant; otherwise, alternative methods can be adopted for ensuring that instruments are not misread. Over the whole range of instrumentation it is important to realize that, despite what has been achieved, an even greater range of measurement and reliability is essential to enable adequate information on the behaviour of the reactor core to be obtained.

Mr. Rumfitt's remarks about cluttering the landscape with obsolete reactors are true, and illustrate one of the reasons which make some of us doubt whether the rush to build so many nuclear power stations of such size as at present is indeed wise, particularly since it is difficult to believe that the future supply of oil can be as unstable as suggested by Mr. Ashworth—if we are to have any future at all.

His comments on the impossibility of preventing some spread of activity are true, but this is a question of degree; and the value of a high sensitivity in the burst-cartridge detection gear lies in the possibility of keeping the level low enough throughout the working life of the reactor.

Without detailing the 'permit to work' system adopted at Calder Hall, the essence can be stated to be similar to that used on chemical plant. In this system responsibility for safety and operation is not separated, but vested solely in the operators; and no item of equipment associated with the plant can be taken off line for maintenance without clearance having been obtained from the appropriate operational supervisor. Where a particular item forms an interconnecting link between two separate parts of the station, clearance must be obtained from both sides; and the responsibility for ensuring that this does not involve any hazard, for indicating the limits of the clearance and for taking any necessary preventative or precautionary measures lies with the operational supervisor.

No undue problems were associated with the outdoor boilers of the Calder Hall reactors, but it should be remembered that, while freezing conditions were sometimes experienced and the external conditions in the form of wind and rain were sometimes extremely trying, this particular stretch of the Cumberland coast seldom experienced any severe and prolonged frosts. The main disadvantages of this form of construction are associated with maintenance operations.

Mr. Vickers will find most of the constructional details in the Calder Hall Symposium. It is true that some build-up of oil in the reactor is unavoidable, but, if held to reasonable limits, there is no reason why it should cause any marked disadvantage, provided that it carries no incompatible elements.

With regard to Dr. Shaw's query on gagging, since the limiting temperature is often the internal uranium temperature, there will probably always be some drop in outlet gas temperature towards the core centre. Theoretically, gags would help to trim the reactor more accurately, but there is a strong case for keeping anything within the reactor vessel mechanically simple and robust, in view of the difficulties of maintenance within the shield. The same applies to any item which has to operate within the reactor core; and the absence noted by Mr. Gabriel of specific mention of prolonged operational testing of the charge and discharge gear before take-over was due to the fact that, throughout the early tests, modifications were continually shown to be necessary. Probably some relaxation in the clean condition standards could be tolerated, but this will not be very great on the natural-uranium gas-cooled reactor, in view of its size, and therefore the difficulty of putting things right after erection, and its tight neutron economy.

DISCUSSION ON

'ELECTRIFICATION OF THE U.K.A.E.A. INDUSTRIAL GROUP FACTORIES'*

Before the North-Eastern Centre *at* Newcastle upon Tyne *8th December, the* Western Centre *at* Gloucester *15th December,* 1958, *a joint meeting of the* Mersey and North Wales Centre *and the* North-Western Centre *at* Chester *2nd February, and the* Tees-Side Sub-Centre *at* Middlesbrough *1st April,* 1959.

Mr. T. H. Morrison (*at Newcastle upon Tyne*): The authors refer to construction supplies and the difficulty of assessing the amount of temporary supply required. On the larger sites this is becoming more difficult when stress-relieving of the pressure vessel is also necessary, for nearly 1·5 MVA is needed to supply the site and the large workshops associated with the pressure vessel and heat exchangers. At Chapelcross it became obvious that temporary Diesel-generators were not practicable to supply 1·5 MVA while stress-relieving, requiring 1·5 MW, was connected to the mains. However, the Electricity Board were prepared to provide 3 MVA on the assumption that heavy-current switching would be carried out during night hours.

Stainless-steel tubes were used as heating elements for stress-relieving, two 3-phase elements being used at Calder Hall and controlled by an l.v. switchboard. It was decided that a single 3-phase element would be used at Chapelcross, and this fact was taken into account when designing the construction supplies. An 11 kV ring main was installed around the site, fed by two 11 kV circuit-breakers. Four substations were connected to the ring main through tee-off fuse and isolator units and 11 kV/415-volt transformers of 750 or 1 000 kVA capacity, depending on their location. The two substations nearer the main 11 kV switches served the reactors.

When a stress relief was pending, an additional tee-off unit was inserted in the ring main, so that there were two units in series at that point. The primary of a 1·5 MVA 11 kV/415-volt transformer was connected to the fused circuit of the tee-off unit and the secondary was connected solidly to the 3-phase heating element, the transformer being placed just outside the pressure vessel to minimize the length of the heavy l.v. cables.

At stress relief the ring main was broken between the two tee-off units, resulting in the construction supplies being fed from one end of the ring and the stress-relief transformer from the other. Switching of the element was carried out at 11 kV, the transformer being able to carry the initial 50% overload for several minutes. The load gradually fell as the element was heated, the relieving temperatures of 600° C being attained in less than two days. The power was then disconnected. This method has been successfully used for four pressure vessels and seems to be perfectly satisfactory, with the chief advantage that supplies are not interrupted at any time.

Mr. P. H. Woodward (*at Newcastle upon Tyne*): I am still not certain to what extent the elaborate supply arrangements at Capenhurst were necessitated by the need for reliability of supply as against the requirement for low impedance to avoid stalling of large motors subsequent to short-term faults. For instance, are the 132 kV feeders of the pair supplying Sections A, B, C and D each sufficient to carry the load of the associated section with the other feeder out of commission? Furthermore, the short-circuit power available on the 11 and 3·3 kV busbars could, under certain circumstances, be exceedingly high, and I should like more details of the arrangements for avoiding such conditions.

It is apparent from the size of the present and near-future loads that the nuclear-engineering industry as a whole has been up to the present, and will be for some time, a consumer of electricity rather than a supplier. I should be interested to know when the industry will be able to furnish a credit balance in the form of an overall export to the nation's electricity supply system.

Mr. E. L. Tapson (*at Gloucester*): I am impressed by the comprehensive alternative arrangements, and should like to know whether all design is carried out by U.K.A.E.A. staff or whether outside consultants are employed.

At Capenhurst the paper shows eight connections to the Grid and to four major power stations, together with three transformers at each main substation. Might some interconnection on the 11 and 3·3 kV sides save much duplicating of the main supplies, bearing in mind fault-energy levels? Has any occasion arisen to prove the necessity of the arrangements so made?

Is there difficulty in obtaining staff of the calibre to match the precautions taken in the plant, and do they stay long enough thoroughly to know and understand the distribution they control?

I note the use of 1 000 and 1 500 kVA transformers where our Board, even in concentrated load areas, prefer 500 kVA units, and I wonder who is right.

With regard to the instability of induction motors on transient faults, I recall a similar problem at a steelworks where the management were particularly concerned at a sudden loss of motive power. The problem here was overcome by building flywheels into the drives. Could a similar solution have been used at Capenhurst?

Mr. J. A. F. Harvey (*at Chester*): My interest lies in the way a large and concentrated load has been fed without permitting excessive fault levels to exist, and we have been told that initially the reactance was slightly high, leading to some difficulty with motors picking up after the clearance of an external 132 kV fault. It is interesting to hear that motor and circuit characteristics were investigated on a simulated circuit driven by a short-circuit testing alternator.

Since the concentrated load at Capenhurst may be regarded as a single large induction motor when a fault occurs, the r.m.s. symmetrical value of the first few loops of current will be substantially higher than the continuing current from the supply source. The conditions of making and carrying the first peaks of current are much more severe than those normally associated with the interrupting duty and are similar to those encountered in power stations. What are the ratios at Capenhurst, and is this one of the less obvious reasons for favouring air-break switchgear? Air-break designs offer great scope for obtaining high making and latching performance, owing to their smaller 'in contact' travel compared with oil circuit-breakers, which, for anything but the lowest ratings, need overlap contacts with relatively long 'in contact' travel.

The problem of keeping the essential load within bounds when it has to be supported by Diesel-generators is obvious, but was any study made using a site where water could be stored for supporting the full load for short periods?

What types of plugs and sockets are used for disconnecting apparatus in danger zones?

Mr. J. H. S. Morris (*at Middlesbrough*): The carbon-dioxide fire-fighting equipment referred to in Section 5.1 is presumably automatic in operation. In this connection the layout of a typical substation given in Fig. 9 shows double outward-opening

* Binns, J. W., and Outram, W. J.: Paper No. 2698 U, August, 1958 (see 106 A, p. 77).

doors to the h.v. switchroom. Are these specially reinforced to prevent them opening in the event of an explosion within the switchroom, with the possible resulting loss of carbon dioxide before extinction of a fire? Might not sliding doors be more suitable?

When reading the paper I assumed that the 6·6 kV/11 kV/415-volt transformers referred to in Section 5.3 were triple-wound units with all three windings energized, but during the presentation of the paper it appeared that they were transformers with primary windings tapped to be suitable for operation at 6·6 or 11 kV. Will the authors confirm that this is so?

In Table 1, for a particular size of motor the cable size specified from fuse to starter is different from that between starter and motor. Will the authors give the reasons for this?

Mr. V. F. Lord (*at Middlesbrough*): With regard to the installation at Capenhurst, did the Authority consider building a local power station specifically for the plant concerned, and distributing electricity by a cable network with no Grid tie? The cable network would be less prone to outage than overhead lines, and as a result, probably less standby equipment would have been required. Furthermore, if a steam demand existed in the factory, this could be supplied from back-pressure generating sets.

I was interested to see that remote control rooms are provided in substations where equipment of 150 MVA and above is used. Is this really necessary for 150 and 250 MVA equipment, since it must add considerably to the cost of the substation?

In Table 1, the discrepancy in cable sizes for standard squirrel-cage motors is presumably because the starter-to-motor cable is protected by the starter overloads, whereas that between fuse and starter is protected by a fuse, which may have a fairly high rating. What was the basis of calculations determining this heavier size of cable?

I was surprised to find that tungsten-filament lighting is used in process buildings. Surely continuous-running plants could easily justify the use of fluorescent or h.p. mercury-vapour lamps.

Mr. D. W. Pattenden (*at Middlesbrough*): I understand 'electrification' to mean the changing over to electrical operation of a mechanically operated factory or other works. Was electrical operation originally thought to be so hazardous or otherwise unsuitable for some of the factories that initially they were equipped with only mechanical, pneumatic or hydraulic actuators?

The authors state that all electrical equipment in the examination caves is connected by plugs and sockets so that it can be removed and replaced if it becomes faulty. They also state that repair is often impracticable, owing to contamination. How is faulty contaminated equipment removed from the caves without hazarding the maintenance personnel, how is it transported and how is it disposed of so as not to constitute a more or less perpetual danger to life? What precautions are taken to ensure that this equipment does not come into the hands of people who may not appreciate its contaminated condition?

Messrs. J. W. Binns and **W. J. Outram** (*in reply*): We would draw attention to the reply to the earlier discussions, and again regret that space limitations prevent our answering questions individually.

Dealing with the many additional questions asked on the Capenhurst system, each feeder of the duplicate 132 kV supplies to each of the sections A, B, C and D at Capenhurst would support the load at that section. Interconnection at 11 or 3·3 kV on the present Capenhurst system cannot be made without affecting fault levels. In fact, certain interconnections did initially exist between the two 11 kV substations and between the 132 kV sections A and B which feed them, but unstable running was experienced under certain circumstances with this arrangement, and present arrangements were chosen in conjunction with the C.E.G.B. as a result of this (see Mr. Eaves's contribution to the discussion in London). No special provision is made to avoid any exceptional high fault power on the 11 and 3·3 kV busbars other than the insistence on great care in testing and switching the circuit back on to these bars after maintenance.

A local generating station for Capenhurst was considered, and in fact the C.E.G.B. station at Ince was built for the purpose. Overhead lines could not be eliminated, however, owing to the need for back-up capacity to local generation. Moreover, the steam demand at Capenhurst is low and in no way lines up with the requirements for electricity.

A number of questions have been asked relating to substation design and choice of switchgear. Mr. Tapson is surprised by the size of medium-voltage transformers chosen, but we suggest that this is primarily a matter of load concentrations and that the Area Boards would probably arrive at similar conclusions if they had similar concentrations.

The 6·6 kV/11 kV/415-volt transformers are, in fact, wound with the primary tapped to permit a series-parallel arrangement on part of the winding.

With regard to the provision of remote-control points for switchgear of 150 MVA or over, it is regretted that there is an error in the paper. It is, in fact, our practice to provide remote control for switchgear of over 150 MVA generally in accordance with the recommendations of H.M. Inspector of Factories.

No special provision is made to reinforce the outward-opening doors of substations which have automatic carbon-dioxide fire protection. Even if these were to open as the result of an explosion, we believe that the carbon dioxide would still be effective.

Some discussion has taken place on the capacity of construction supplies and the general statements are noted. It is pointed out, however, that on our sites we have very little to go on when first opening up a new project, and the paper indicates what has been found generally suitable for normal work. Special provision must inevitably be made for stress-relieving or other special applications when these are necessary.

Water power for emergency generation has not been resorted to or considered, primarily because the sites are not suitable. In addition, we feel that the capital cost of such a scheme for emergency generation would far outweigh the cost of Diesel generation.

The cable sizes in Table 1 of the paper are based on our interpretation of The Institution Wiring Regulation No. 316 (13th edition) and are on the basis that the cable between the fuse and starter is rated for the full-load current of the motor or half the fuse rating, whichever is the greater, and the cable between the starter and the motor is rated to the full load current of the motor.

Faulty electrical equipment in examination caves, etc., is connected by normal types of industrial plugs and sockets to enable removal by men dressed in special 'frog suits' or by remote-handling equipment.

Fluorescent and h.p. mercury-vapour lamps are, in fact, used for many of our process plants, although the preference for operational reasons is frequently for tungsten-filament lamps.

Although the nuclear engineering industry as a whole has, up to the moment, been an overall consumer of electricity rather than a supplier, with the operation of the Calder Hall A and B power stations and the gradual loading up of the Chapelcross station, a near balance is imminent. With the commissioning of the C.E.G.B. stations, the industry as a whole will be a supplier.

In general, design work for U.K.A.E.A. factories is carried out by our own staff. Outside consultants are, however, employed in certain instances. As in other industries, we have our difficulties in obtaining suitable technical staff, but in spite of this we appear to have managed fairly successfully, probably because we are a new, and to some extent novel, industry.

DISCUSSION ON 'ELECTRICAL INSTALLATION AT CALDER HALL NUCLEAR POWER STATION'*

NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 17TH MARCH, 1959

Mr. J. O. Joss: The electrical design of Calder Hall was strongly affected by the requirement that full plutonium production should proceed with or without the generating plant in operation. A further complication was the decision to contribute from the works supply to the adjacent Windscale factory. The final power station, not surprisingly, resembles an industrial power plant more than a modern central power station.

A distinctive feature of Calder Hall is the use of Ward Leonard sets for blower-motor supply. This d.c. system is feasible because of the use of low-speed centrifugal-type blowers, and because the off-load fuel-charging system gives no dearth of shut-downs for brush-changing. Obviously, even these circumstances are inadequate, and arrangements have been made for single-unit outages for rebrushing. Is information on brush life and frequency of circulator shut-down for this reason available?

The majority of the civil stations are equipped with axial-type circulators, which are high-speed machines requiring an a.c. drive. In two of the stations the drive is by induction motor, with speed control from variable-speed house turbo-generators. Thus the circulator load is removed from the normal auxiliary electrical system, which is of a very conventional design. In a 300 MW nuclear power station with a total circulator load of 30 MW, the constant-frequency auxiliary load is only 12 MW. The analysis for this, namely 4 MW for circulating water, 3 MW for reactors, 4 MW for the turbine hall and 1 MW for services, should be compared with Table 1 in the paper. Since the reactor electrical load is small (1·5 MW for each reactor), it is supplied at 415 volts, and all 3 kV switchgear is confined to the turbine hall, as in conventional practice.

Central power stations from their inception have included storage batteries for shut-down and emergency use. In large power stations these are kept small by using Diesel-generators to take over the load after a short time. Calder Hall uses such a system, but of very large relative capacity. The use of a completely d.c. system has disadvantages associated with voltage variation, high current and fault interruption. Increased maintenance may be difficult to achieve if plant is in a high-radiation zone. The addition of inverting plant supplying an a.c. system is more convenient and economical and no less reliable. The use of brush-gear is confined to a minimum, and this operates under near-ideal atmospheric conditions and is accessible for maintenance without affecting auxiliary drives.

Mr. P. Balmer: It may be of interest to look at some of the details of the low-frequency supply system for the control-rod actuating motors. Four 3-phase frequencies are required. A 3-phase motor drives an alternator directly and a frequency-convertor rotor through a 1:1 gearbox. The alternator output is fed to six slip-rings on the convertor to produce a rotating magnetic field which spins at synchronous speed with respect to the convertor rotor. The rotor windings are brought out to a commutator with fixed brush-gear. If the rotor were stationary, an output at 50 c/s would appear at the brush terminals. If the rotor is spun backwards at the same rate as the field spins forward, a d.c. output will be obtained. The magnitude of the voltage at each output terminal is determined by the position of the rotor in relation to the alternator rotor. Small differences in relative speed of convertor rotor and alternator will produce low frequencies at the output.

For safety reasons the phase rotation and frequency of the output must be accurately defined. The gearbox is an in-line differential unit, the input and output speed difference being controlled by the cage. This is either driven through one of three fixed gear trains or held stationary by a brake. Gear-train selection is effected by stationary-field electromagnetic clutches, only one of which is energized at any one time. If the direction of rotation of the pilot motor driving the cage is incorrect, the control rods might be pulled out at 100 times too high a speed. To safeguard against this a free-wheel is incorporated in the drive. If the main motor phase is reversed, both alternator and frequency-convertor reverse, so that the output phase sequence is not affected, provided that the pilot motor rotates in its usual direction. Normally, if the drive to the convertor is sheared but the alternator is still driven, the phase sequence will drive the control rods in. Under conditions of reversed supply to the main driving motor the rods could be pulled out by the drive failing, but this is a double fault. In general, it is impossible to protect a system against simultaneous double faults. Protection outside the system would then be relied upon, e.g. the emergency shut-down circuits. Failure of the main supply simply makes the machine set run down over a period of minutes.

Rotary converting equipment is thought to be undesirable, since to hold the rods at 0 c/s the set must run continuously, but to maintain reasonable continuity of supply some static converting equipments are fed from local flywheel alternator sets and hence their advantage is not so obvious.

Messrs. N. J. Mackay and **E. Hardwick** (*in reply*): We cannot give Mr. Joss a simplified statement of brush life on circulator motors, since a certain degree of random wear is being experienced. It has been found useful to arrange outages of single machines after 8–10 weeks of continuous operation for brush and commutator maintenance if there has been no intervening shut-down for other reasons. However, considerable work is still proceeding on the solution to the various problems involved with a view to the extension of this period.

We are pleased to see comparative figures for house load relative to a large C.E.G.B. nuclear station, presumably Bradwell.

We have already given some of our reasons for the selection of a d.c. emergency system in previous replies. The advantages claimed by Mr. Joss for an a.c. scheme are offset to some degree by the fact that the inverter plant must run continuously, even though a large proportion of the load may be stationary under normal conditions.

We acknowledge Mr. Balmar's contribution in amplifying some of the interesting detailed points in the design of a control-rod system. Presumably the reference to flywheel alternators is intended to indicate the need to prevent the dropping of control rods because of supply transients. It may be possible to utilize the battery system as a form of 'holding' supply to overcome this problem.

* MACKAY, N. J., and HARDWICK, E.: Paper No. 2699 U, August, 1958 (see 106 A, p. 245).

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ELECTRICAL SUPPLIES TO POWER STATION AUXILIARIES

By D. A. DEWISON, Associate Member.

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SUMMARY

The paper considers the factors involved in the design of electrical supplies to power stations.

The general principles of the unit transformer system are described and the detailed design problems and economic aspects associated with the scheme are examined, being illustrated by an example of a station comprising five 200 MW units.

(1) INTRODUCTION

The electrical load required for running a power station is of the order of 4–7% of the station output.

The safety and continuity of output of the station depend on the reliability of the electrical supplies to the auxiliaries, so that careful consideration must be given to the design of the electrical distribution system. Reliability represents the primary quality of the distribution system and it is evident that complicated systems accentuate troubles in the event of an emergency; hence simplicity is a quality which tends to increase reliability.

The investigation of costs can be reduced to a matter of figures which have to be compared with the more intangible factors of reliability and operational flexibility. This takes the consideration out of the purely electrical aspect into that of the wider conception of power station design. It requires a careful consideration of the relative importance of auxiliaries, and in particular of the problems associated with the boiler feed pump.

A factor influencing the design of the electrical distribution system is the present practice of designing stations on the unit principle, where one boiler and one turbine with the associated auxiliaries run as an entirely separate unit without interconnection. As a natural consequence the electrical supplies have followed the same principle.

(2) THE SOURCE OF SUPPLY

There are four possible sources of supply for auxiliaries:

(*a*) Connection from the Grid system through transformers.
(*b*) Generator terminals, through transformers.
(*c*) Auxiliary generators coupled to main sets.
(*d*) Separately-driven generators (either steam or Diesel).

Nearly all the combinations of these sources have been tried, but the one now adopted in this country is a combination of (*a*) and (*b*), which has come to be known as the unit transformer system.

Of these methods, (*d*) is much the most expensive, while there is a small difference between (*b*) and (*c*). Method (*a*) is expensive and is also considered to be insufficiently reliable on its own; it is now only used in combination with (*b*). There might be a case for considering (*a*) in a station comprising only two units. A cost comparison for (*b*) and (*c*) is shown in Appendix 15.1.

The merits of these schemes have been discussed at length in a paper by Szwander.*

* SZWANDER, W.: 'Power Supply for Generating Station Auxiliary Services', *Journal I.E.E.*, 1947, 94, Part II, p. 372.

Mr. Dewison is with the Central Electricity Generating Board.

(3) THE UNIT TRANSFORMER SYSTEM

Fig. 1 illustrates a distribution system for a power station comprising five 200 MW units. The essential features of the scheme are as follows:

(*a*) There are two main sources of supply: from the Grid via the station transformers, and from the generators via the unit transformers.

(*b*) The auxiliaries are divided into two main groups: 'urgent' auxiliaries, i.e. those associated with the running of a unit, and 'service' auxiliaries, i.e. those whose loss would not affect the output of the station until after a considerable time interval.

(*c*) The urgent auxiliaries are supplied from the unit transformers and the service auxiliaries from the station transformers. Each unit has an entirely separate supply and failure of one unit does not affect any of the others. This method of dividing the urgent and the service auxiliaries gives greater reliability to the urgent auxiliaries, because disturbances and faults on the less important service auxiliaries are not reflected to the unit supplies. Furthermore, the unit transformer is a more reliable supply than the station transformer, because failure of the Grid system will not affect the unit supplies if the sets can be kept running.

(*d*) Paralleling can only be made at the 6·6 kV switchgear, the method of connection making it impossible to parallel at the 415-volt level.

(*e*) Interconnection is provided between the station boards and the unit boards for starting purposes and to provide an emergency standby supply in the event of failure of the unit supplies.

(*f*) A continuous supply is given to the standby-boiler feed pump, and facilities are provided for readily transferring this auxiliary to the unit transformer when it has come into operation.

(*g*) A reactor is included between the station transformers, and the switches on the station board are interlocked to ensure that the two transformers cannot be paralleled unless the reactor is inserted. This is done to reduce short-circuit forces, as explained in Section 12.

(*h*) Duplicate supplies to the sub-branches of the unit circuits have not been provided for the station shown in Fig. 1, as it was felt that the reliability of switchgear, cables and transformers is such as not to warrant the increased cost and complications. However, this aspect requires careful consideration for each station. For instance, failure of a transformer might cause the outage of a unit, and the cost of the possible outage for a high-efficiency machine has to be assessed against the cost of the method of restoring the unit to service. One method of reducing the time of outage is to have available in the station stores a spare transformer and switch. A more expensive method, which reduces outage time to a minimum, is shown in Fig. 5, where a built-in standby is provided.

(4) METHOD OF OPERATION

To start up a unit, a supply is taken from the Grid via the station board to the unit board, the unit transformer switch being open. When the generator has been brought up to normal speed it is synchronized on to the main transmission busbars

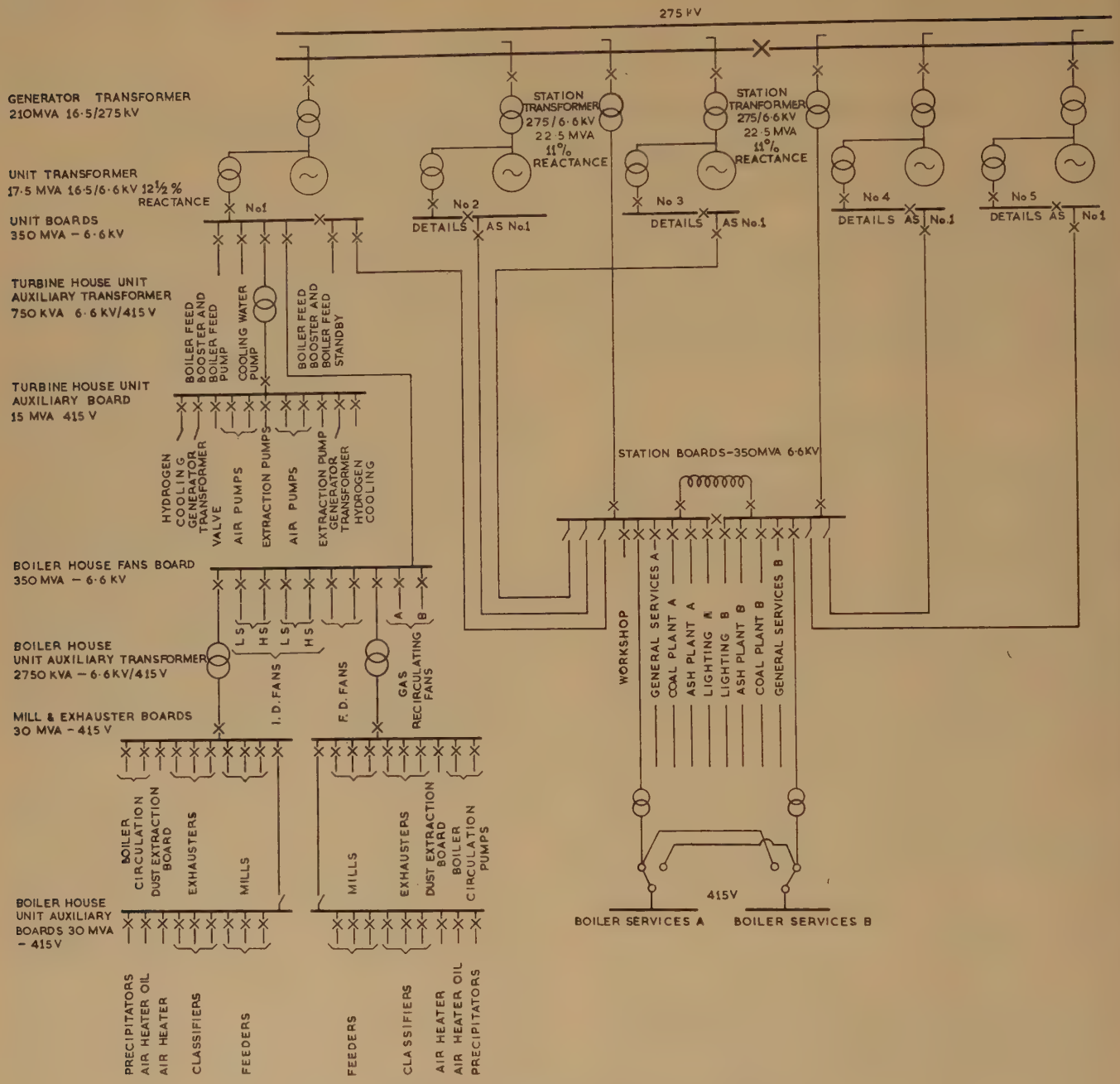


Fig. 1.—Auxiliary power supply connections: 5 × 200 MW units.

and very lightly loaded. The unit supply and station supply are check-synchronized and the two sources paralleled. The station board supply is then disconnected from the unit board, leaving the urgent auxiliaries supplied from the unit transformer.

The reverse process is carried out for shutting down the unit.

(5) DIFFICULTIES OF PARALLELING AND CONNECTION TO THE GRID

Although in practice little difficulty is experienced in paralleling the unit and station supplies, due regard must be given to this in the early stages of design.

Normally the main Grid busbars are operated with the bus section switch closed, but there may be occasions when it is necessary to open this switch and operate the Grid as two separate systems. If it is found necessary under these conditions to parallel a unit on one section with a station transformer on the other section, then the two sections of the Grid are paralleled through the 6·6 kV switchgear. Under these conditions it is possible that circulating currents will pass through the auxiliary transformers. It is necessary to ensure that these currents are within the operating limits of the transformer circuits.

At some station sites, usually where a new station is to be erected alongside an existing one, it is possible that the existing Grid switchgear could be utilized to supply the station transformers. Thus it is possible that the new station generators would be connected to a new 132 kV or 275 kV switching station while the station transformers were connected to the existing

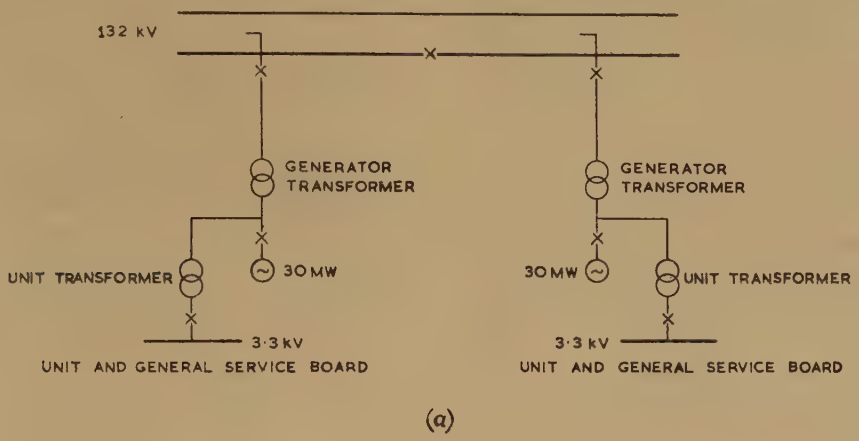
33 kV. There are considerable economies to be made by this arrangement, but these have to be assessed against the reduced reliability, and the difficulties of paralleling mentioned above.

(6) VARIATIONS ON THE UNIT TRANSFORMER SCHEME

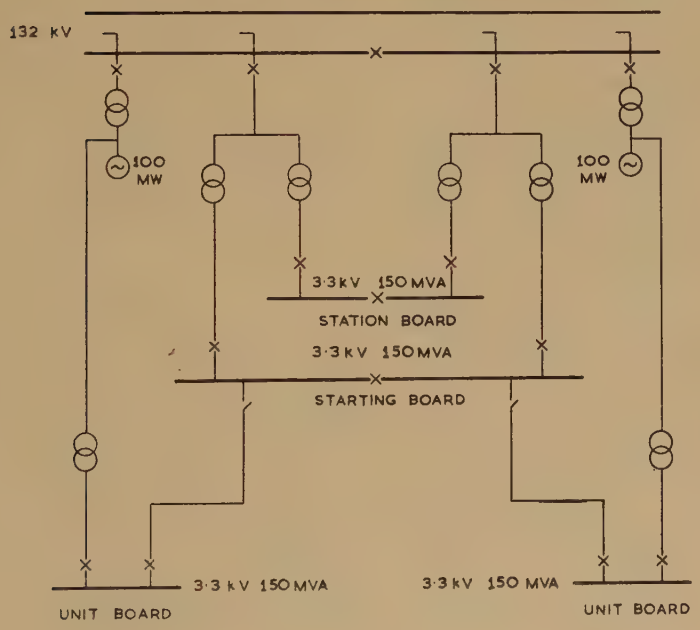
Two variations on the scheme shown in Fig. 1 have been used. Fig. 2 shows the alternative methods.

That shown in Fig. 2(*a*) has been used at a station comprising four 30 MW units. With this method the station transformers are eliminated. A switch is inserted between the generator and the generator transformer, and is opened for purposes of starting up. The unit auxiliaries then obtain their supplies through the generator and unit transformers. The method has the following disadvantages: (*a*) For sets much above 30 MW the currents would become excessively large and special switchgear would have to be developed. (*b*) The introduction of a switch into the main circuit of the unit reduces reliability. (*c*) There is no standby supply, which is very important for boiler feed pumps on larger units. (*d*) The desirable unit principle is lost, because the general-service auxiliaries must be supplied from the unit transformers and this factor leads to a complicated system of connections, with large-capacity unit transformers.

The method shown in Fig. 2(*b*) has been used at a station comprising six 100 MW units. This method allows the auxiliary switchgear rating to be reduced, but the associated cost saving is offset by the cost of the additional transformers, and the difference in overall cost of the scheme is marginal compared with the method of Fig. 1 when all the factors are taken into account. Where the main Grid voltage is 275 kV the scheme loses its economic merit because of the high cost of the transformers.



(*a*)



(*b*)

Fig. 2.—Variations on unit-transformer scheme.

(7) CLASSIFICATION OF AUXILIARIES

As mentioned in Section 3, the auxiliaries are classified into two main groups for purposes of power supply: urgent auxiliaries

and service auxiliaries. The urgent auxiliaries are those associated with the running of a unit, i.e. boiler and turbine, whose loss would cause immediate loss of station output.

The service auxiliaries are those whose loss would not affect the output until after a considerable time interval. Included in this group are those auxiliaries which, while associated with a unit, are not urgent, such as the barring gear and auxiliaries used for starting up the unit.

In order to determine into which group each auxiliary should be classified, it is necessary to examine their functions and operations and to appraise their relative importance. It is not intended here to investigate this in detail, but only sufficiently to indicate into which group each auxiliary should be placed. The more important auxiliaries commonly in use at pulverized-fuel stations only have been considered.

(7.1) Boiler Feed Pumps

Various systems of boiler feed pumps have been tried at different times, but the one most favoured in recent designs has been two 100% electrically-driven pumps, one acting as standby to the other. In the event of failure of the normal running pump the standby is automatically started by a feed-pressure relay. The normal running pump is supplied from the unit board, while the standby pump is supplied from the station board; thus a complete loss of boiler feed can only occur if the station supply and unit supply are lost simultaneously.

On recent large high-pressure units the boiler feed pump has been split into main pump and booster pump, but this has had little effect on the electrical distribution considerations as both are fed from one switch.

(7.2) Extraction Pumps

It is usual to install two 100% extraction pumps per machine, one running and one standby. A pump failure would cause the water level in the condenser to rise, and in a matter of some minutes it would reach a dangerous position necessitating a unit shut down. No automatic change-over feature is fitted to these pumps, the time interval being considered sufficient to enable a change-over to be made by hand.

Both these pumps are supplied via the unit board. The case for supplying one of them via the station board is not as strong as with the boiler feed pumps because neither can be regarded as a definite standby, and automatic change-over is not fitted.

(7.3) Boiler Fans

The normal practice is to install two induced-draught and two forced-draught fans per furnace, each working at full load when the boiler is at continuous maximum rating (c.m.r.). With modern boilers it is possible to run the unit at reduced load in the event of failure of one of the fans, although it is anticipated that this condition would not be allowed to continue for any length of time.

All fans should be supplied via the unit board.

(7.4) Milling Plant

The milling plant usually comprises the mill, primary air fan (or exhauster), coal feeder and separator (or classifier). It is usual to install one standby mill unit per boiler; for instance, a 200 MW unit boiler would probably have six mill units, five of which would be capable of handling the coal requirements of the boiler at c.m.r.

The milling plant requires more maintenance than any other auxiliary in the station, and for that reason the running and standby units are frequently interchanged.

The loss of all the mills would necessitate a shut-down of the boiler, but loss of only one mill would merely reduce output. For this reason a strong case could be made for supplying half the mills via the unit board and the other half via the station board. However, when the economics of such an arrangement are considered, and bearing in mind the added complication to the whole distribution system, on balance it has been found preferable to supply all the mills via the unit board.

(7.5) Electrostatic Precipitator

The loss of a precipitator has no serious effect on unit output, so that its supply is not of such great importance as that to the other unit auxiliaries. However, for amenity reasons, and in view of the fact that precipitators are in continuous operation with the unit, the more reliable unit board supply should be given to them.

(7.6) Cooling Water Pumps

The arrangement of the cooling-water system varies in different stations, but it is usual to have a bus system.

With this system the cooling-water intake is taken to a common chamber whence a number of pumps discharge into a bus main supplying all the condensers in the station. The number of pumps installed is usually equal to the number of turbo-generator units, each pump being capable of delivering the required quantity for one unit.

Since the pumps are common to all the units, consideration has been given to providing them with an electrical supply from the station board. However, because of the vital importance of the cooling water to the station output and in preventing plant damage, a separate supply to each of the pumps from the respective unit boards is justified.

(7.7) Turbine Barring Gear

The barring gear is normally motor driven, its function being to keep the turbine rotor slowly rotating during periods of warming-up and cooling.

Since the turbo-alternator is not supplying power to the unit transformer whilst the barring gear is in operation, this auxiliary is fed from the station supply.

(7.8) Turbo-Generator Oil-System Auxiliaries

The auxiliaries fitted to a typical turbine oil-system consist of a main oil pump mechanically driven from the turbine shaft, and an a.c.-motor-driven full-duty oil pump for starting up and the provision of automatic standby. In order to avoid the necessity of running the full-duty auxiliary oil pump during barring, an a.c.-motor-driven flushing-oil pump, capable of maintaining the requisite supply of lubricating oil only, is provided. In addition, to ensure a supply of lubricating oil in the event of failure of the a.c. supply, a d.c.-driven flushing-oil pump fed from the station battery is provided, and arranged to cut in automatically in the event of oil pressure falling to a specified figure. A high-pressure oil jacking pump is usually installed to supply oil for lifting the rotors in the bearings in order to reduce the starting torque on the barring motors.

On hydrogen-cooled generators the hydrogen seals are maintained by oil from the lubricating system, but when the unit is shut down an a.c.-motor-driven seal-oil pump is brought into service. The importance of maintaining the seal is such as to warrant a standby d.c.-motor-driven seal-oil pump being provided to cover failure of the alternating current supply.

An oil purifier is connected in such a manner that it can be used when the turbo-generator is either running or shut down.

All these electrically-driven auxiliaries are used either for starting purposes or standby duty, the mechanical pump being the normal running auxiliary. All the a.c.-driven pumps should therefore be connected via the station board.

The d.c.-driven pumps, if supplied from the station battery, will only protect the unit for as long as the battery capacity lasts. With the increase in size of units, consideration has been given to providing a standby Diesel-alternator for giving an alternative supply to the a.c. flushing pump and seal-oil pump. If a Diesel is installed the battery capacity can be reduced and the resultant saving in cost could contribute to the cost of the Diesel.

In very large stations it is probable that a Diesel set could be justified.

(7.9) Hydrogen Cooling

The generators of modern units are cooled by circulating hydrogen through them, the hydrogen being cooled by passing through a water cooler. A closed cooling-water circuit is usually provided to ensure that the water passing through the water/hydrogen cooler is of sufficient purity. The closed-circuit water passes through water/water coolers, the cooling water for these usually being supplied from the main cooling-water system.

Two 100% motor-driven pumps are usually provided for circulating the water in the closed circuit, one acting as standby. Failure of the normal running pump causes the generator temperature to rise, but there is sufficient time available to allow a change-over to the standby to be made by hand.

Both these pumps are supplied from the unit board.

(7.10) Generator Transformer Cooling

Large generator transformers are usually cooled by the transformer oil passing through oil/water coolers, the water being obtained from the main cooling-water system. The oil is assisted in its circulation by motor-driven pumps.

There are usually two 100% or three 50% oil pumps per transformer, one acting as standby. The time margins on temperature rise, on loss of one of the oil pumps, are usually sufficient to allow a change-over to the standby to be made by hand, but there has been a recent trend towards making the change-over automatic.

These pumps are supplied from the unit board.

(7.11) General Service Auxiliaries

The auxiliaries in this group are shown in Table 2.

The loss of any of these auxiliaries has no immediate effect on station output. In the case of coal and ash plants, coal-bunker and ash-hopper capacity normally gives considerable time for adjustments to be made in the event of an electrical supply failure.

All these auxiliaries are supplied via the station board. Duplicate supplies are provided primarily because of the necessity for an alternative supply during times of maintenance, although, incidentally, the alternative supply would prove valuable in certain circumstances such as the failure of a transformer when the coal bunkers were nearly empty.

(7.12) Lighting and Heating

It is necessary to ensure that the lighting supply be maintained continuously. Two transformers connected via the station boards provide the normal supply, each being capable of carrying the full load.

In the event of failure of the Grid supply an automatic change-over switch operates to give a supply from the station batteries to certain vital lights throughout the station.

(8) BATTERY SUPPLIES

The station batteries are used to supply the emergency lighting, standby turbine oil-flushing pump, standby seal-oil pump and turbine governor motor at 240 volts; the switchgear tripping and closing supplies and the indicator lamps and alarms at 110 volts, and communication circuits at 50 volts.

Where the use of 110 volts for the switchgear-closing solenoids will result in excessive voltage drop in the leads, the alternative of 240-volt closing solenoids has to be considered.

The battery rating will depend on the loads to be catered for, and as a guide, an emergency lighting period of 3 hours will in most cases be required.

As mentioned in Section 7.8 the possibility of providing a standby Diesel supply for the flushing pump and seal-oil pump would reduce the battery capacity required.

(9) THE CHOICE OF VOLTAGE

The power consumed at large stations is too great to be controlled at the normal industrial voltage of 415 volts, and 3·3 kV and 6·6 kV have been used, while 11 kV has been considered. These higher voltages are stepped down to 415 volts for the small auxiliaries.

For units up to 120 MW it has been found that 3·3 kV can usually deal with the load, but beyond this 6·6 kV becomes necessary. On economic grounds, 3·3 kV is generally the cheaper system up to 120 MW units, but at this size the difference in cost is marginal between 3·3 kV and 6·6 kV, with 6·6 kV usually proving slightly cheaper. Appendix 15.2 shows a cost comparison based on the connections shown in Fig. 6. For 200 MW units, 11 kV has been considered, but has been found to be slightly more expensive than 6·6 kV.

Some years ago certain C.E.G.B. power station plant specifications were standardized, and for this purpose it was desirable to state which motors should be at 415 volts and which at the higher voltage. This problem has to be considered in relation to the distribution system as a whole. For instance, there is a limit to the amount of load to be put on the 415-volt system, set by the switchgear rating and voltage regulation, unless complicated and expensive subdivision is made.

An economic investigation coupled with a consideration of the above factors led to the adoption of the following standards:

(*a*) Where the main voltage is 3·3 kV, motors up to 150 h.p. to be at 415 volts.

(*b*) Where the main voltage is 6·6 kV, motors up to 300 h.p. to be at 415 volts.

It is probable that at present-day prices the 150 h.p. figure might be raised slightly.

These values have not been strictly adhered to in all cases, as it may be advantageous to go outside the limits in certain circumstances.

(10) SWITCHGEAR

Air-break and oil-break switchgear are the two main types used at the present time.

Oil-break switchgear has the inherent disadvantage of fire risk. Furthermore, it is more difficult to maintain although no reliable statistics are available on costs. Provided the capital cost differential is small, air-break switchgear is usually preferred.

B.S.116 gives a wide variety of choice in current and MVA rating for oil-break switchgear, but in the design of systems it has been found desirable in some instances to go beyond the limits of the recommended ratings. Switchgear for use in this country is usually manufactured to British Standards and the ratings are therefore the same. However, switchgear with ratings above those quoted in British Standards are manufactured. There is no comparable British Standard for air-break switchgear and the ratings available are not so numerous as in oil-break.

So far, it has not been found necessary to go beyond the limits

of 31 MVA at 415 volts, and while there is a switch available to deal with a continuous current of 5000 amp at this voltage, circuits in power stations have not yet reached this figure; 15·6 and 26 MVA ratings are commonly used at this voltage.

At 3·3 kV the maximum rating of switchgear required has been 250 MVA with current ratings up to 2400 amp; 150 MVA gear is the most commonly used rating at this voltage.

At 6·6 kV, switchgear having ratings of 250 and 350 MVA with current ratings up to 2400 amp is available, and systems have been designed to keep within these limits.

At 415 volts there is the further choice of contactor-type switchgear. The short-circuit current of this type of gear is interrupted by fuses, the contacts on the gear merely dealing with normal load currents. It has the advantage of being considerably cheaper than the switchgear which breaks the short-circuit current. Its main application has been for smaller motors up to approximately 100 h.p.

So far, this range of switchgear has proved adequate for power station distribution systems, but 11 kV, 350 MVA or 500 MVA gear, which is available, may be required for larger units.

It will be appreciated that this wide variety of choice gives scope for considerable economic study in designing the distribution system. Appendix 15.3 shows a cost comparison for five schemes, based on the connections shown in Fig. 1.

(11) ANALYSIS OF LOADS

The electrical loads of a power station cannot be calculated with precision from pure design data. In the design of new plant, the friction-drop calculations are complex and most designers tend to install a motor larger than is required in practice, although the margins have been cut down in recent years. Furthermore, allowances have to be made for variations in the type of fuel, and for the condition of the plant after it has been in service for a number of years. A detailed study of this problem is contained in a paper by Kennedy and Hutchinson.*

The motor ratings as given in the tenders for the various items of power station plant are the basis for assessing the load. If these motor ratings are reduced by 10% this usually gives a reasonable estimate of the load. As a check against this, calculations can be made from mechanical data in arriving at horse-powers.

Operational statistics of plant already in service can be a useful guide in assessing loads, and by extrapolation can be used for initial design study before tenders are received.

The following estimates are based on a station comprising five 200 MW units.

A detailed analysis of the unit load is given in Table 1. This

* Kennedy, G. F., and Hutchinson, F. J.: 'Power Station Auxiliary Plant', *Proceedings of The Institution of Mechanical Engineers*, 1956, 170, p. 341.

Table 1

Unit Loads

Service	Motor rating						C.M.R. loading		Starting load	
	Voltage (V)	B.H.P.	Efficiency	Power factor	Full-load current (I)	$\sqrt{3}VI$	Number of motors run	Estimated load	Number of motors run	Estimated load
	volts		%		amp	kVA		kVA		kVA
I.D. fan H.S. } two speed	6600	2140	94·8	0·89	165	1890				
I.D. fan L.S. }	6600	1090	94·3	0·83	91	1040	2	1872	2	940
F.D. fan	6600	662	94·5	0·9	50·5	575	2	1035	2	510
Gas recirculation	6600	412	94	0·9	31·5	360	2	648	—	—
Exhauster	415	440/130	90	0·88	576/165	414/119	5	1400	1	280
Mill	415	300	93·5	0·89	374	269	5	1209	1	242
Coal feeder	415	3·3/0·52	64	0·8	6·1	4·4	5	20	1	4
Separator	415	18/7	75	0·9	27·7	20	5	90	1	18
Air-heater oil pump	415	1	78	0·76	1·75	1·3	2	2	2	2
Air heater	415	10	87	0·83	14·5	10·4	2	18	2	18
Boiler circulating water	415	240	94	0·89	290	208	3	560	3	350
Dust extraction booster	415	10	87	0·83	14·4	10·4	8	72	4	36
Precipitator	415	—	—	—	—	120	1	120	1	120
Total for boiler								7046		2520
Extraction pump	415	245	93	0·88	305	220	1	198	1	198
Q.S. air pump	415	160	93	0·85	198	142	—	—	1	130
Air pump	415	125	92	0·9	155	112	3	302	2	200
Hydrogen cooling-water pump	415	27·5	87·3	0·88	37	26·6	1	24	1	24
Hydrogen seal-oil pump	415	7·5	87	0·84	11·3	8	—	—	1	5
Transformer oil pump	415	6	81	0·9	8·5	6	2	10	2	10
Main oil pump	415	110	89	0·91	131	94	—	—	1	82
Jacking pump	415	7·5	85	0·74	12·5	9	—	—	1	9
Barring gear	415	25	88	0·86	34	24·5	—	—	1	22
Total for set								534		683
Boiler feed pump	6600	6150	97·5	0·91	451	5150	1	4635	1	4000
Boiler feed booster	6600	1575	96·8	0·9	118	1350	1	1215	1	1000
Total for boiler feed								5850		5000
C.W. pump	6600	2350	96·3	0·87	184	2100	1	1890	1	1890
Total for unit								15320		10093

ndicates a load of approximately 15 MVA, i.e. approximately 5·75% of unit capacity, which compares with the 4–6·5% obtained in practice at stations of a lower unit capacity at present n service. These estimates are primarily made for assessing the ransformer size; hence there may be a tendency to err on the side of over-estimating and it is probable that the figures would be reduced in service.

In assessing the size of the unit transformer to carry this load, allowance must be made for later variations in the design of the plant, changes in the conditions of the plant, variations in fuel and errors in estimating. For the station under consideration, 17·5 MVA was chosen, giving an adequate margin for these variations.

The station transformer has imposed upon it the loads for starting-up units, the general services load and the standby loads, and its total load is more difficult to estimate.

Table 1 gives the estimated starting load of one unit, while Fig. 3 shows it in graphical form. It will be noticed that a peak starting load of 10 MVA has been estimated, which is 65% of the estimated full load. The graph shows the starting procedure for a cold start; a hot start would have a much reduced time scale. When starting more than one unit it is possible to prevent the peak loads coinciding if a time lag is made between starts.

The general services load, which will be different for every station, is shown on Table 2. Coal- and ash-handling plants, for instance, differ considerably, and attempts to obtain empirical formula in terms of kilowatts per ton of coal can be misleading. The only satisfactory way of assessing the load is to examine each item of plant and its method of operation.

Table 3 shows the loads imposed on one station transformer. An assessment of these figures gives a guide to the size of the station transformer to be chosen, but there are other factors influencing this decision, as will be made clear in Section 12. A size of 22·5 MVA was chosen, and this will meet most of the conditions of load in Table 3 if advantage is taken of the overload capacity of the transformer.

It should be noticed that the loads in Table 3 could be reduced if the standby boiler feed pump load were transferred to the unit transformer as soon as it was in operation. The load shown as 10 MVA for starting a unit is a maximum, this maximum lasting for approximately 1½ hours for a cold start, but approximately 30 minutes for a hot start. The figures in Table 3 take no account of the possible reduction in load due to time-lagged starting of units.

The most onerous conditions arise when one station transformer is out of service and the other is carrying the c.m.r. load of a unit plus the starting load of another unit, i.e. conditions 11 and 13 in Table 3. In these emergency circumstances it would be possible, if necessary, to arrange for some of the general service load to be shed. Statistically, this condition will rarely arise in practice. It will be appreciated that under normal conditions there would be two station transformers available, so that there would be no difficulty in meeting all the loads shown in Table 3, and the system could start up four units simultaneously.

Table 2

SERVICE LOADS: ESTIMATES FOR TRANSFORMER LOADING

Service	Maximum load	Normal load	Allowance for transformer loading	Allowance with diversity
	kVA	kVA	kVA	kVA
Ash Plant	2 100	2 000	2 100	2 100
Coal Plant	1 800	1 500	1 500	1 500
Boiler House				
Valves	250	0	40	500
Cranes	35	0	20	
Oil lighting-up plant	300	0	300	
Oil tank heaters	900	0/300	300	
Chemical injection	50	0	10	
Boiler control air supply	90	90	90	
Drains	15	0	15	
Turbine House				300
Drains	350	60	150	
Turbine oil system	40	30	30	
Fire protection plant	120	0	100	
Chlorination plant	27	0/27	27	
Valves	50	0/50	20	
Evaporator plant	60	60	60	
De-aerator heaters (off load)	250	0	50	
Lifts	60	30	30	
Cranes	280	0	100	
Water Treatment Plant				
General auxiliaries	85	85	85	85
Crane	26	0	0	
River-Water Make-Up Pump House				
Screens and pumps	330	200	330	330
Crane	35	0	0	
Cooling-Water Pump House				
Valves	72	0	20	20
Crane	35	0	0	
Lighting and Heating	300	150	200	200
Canteen	320	250	300	300
Total	7980	4832	5877	5335

Table 3

200 MW Units: Loading and Voltage-Drop Conditions

	Conditions postulated	Normal loads			Boiler feed pump: motor-starting condition				Steady load after starting b.f.			
		MVA	Total MVA	% Volts	Conditions postulated	MVA	Total MVA	% Volts	Conditions postulated	MVA	Total MVA	% Volts
1	General services ..	5	15	101	General services ..	5	40	87	General services ..	5	15	101
	Start No. 1 set on station transformer	10	0·85 p.f.		Start No. 1 set (without b.f.)	5	0·4 p.f.		Start No. 1 set ..	10	0·85 p.f.	
					Start No. 1 b.f. ..	32·5						
2	General services ..	5			General services ..	5	36	89	General services ..	5	10·9	
	Run No. 1 set on unit transformer		5	104	No. 1 set standby b.f. comes in	32·5	0·33 p.f.		No. 1 set standby b.f..	5·9	0·85 p.f.	102
	No. 1 set standby b.f. comes in		0·85 p.f.									
3	General services ..	5			General services ..	5			General services ..	5		
	Run No. 1 set on unit transformer		15		Start No. 2 set ..	10	44·5	86	Start No. 2 set ..	10	20·9	99·5
	Start No. 2 set ..	10	0·85 p.f.	101	No. 1 set standby b.f. comes in	32·5	0·47 p.f.		No. 1 standby b.f. ..	5·9	0·85 p.f.	
	No. 1 set standby b.f. comes in											
4	General services ..	5			General services ..	5			General services ..	5		
	Run No. 1 set on unit transformer		5		Standby b.f.	32·5	36	89	Standby b.f.	5·9	10·9	102
	Run No. 2 set on unit transformer		0·85 p.f.	104			0·33 p.f.				0·85 p.f.	
	No. 1 or No. 2 standby b.f. comes in											
5	General services ..	5			General services ..	5			General services ..	5		
	Run No. 1 set on unit transformer		15	101	Start No. 3 set ..	10	44·5	86	Start No. 3 set ..	10	20·9	
	Run No. 2 set on unit transformer		0·85 p.f.		Standby b.f.	32·5	0·47 p.f.		Standby b.f.	5·9	0·85 p.f.	99·5
	Start No. 3 set ..	10										
	No. 1 or No. 2 standby b.f. comes in											
6	General services ..	5			General services ..	5			General services ..	5		
	Run No. 1 set on unit transformer				Standby b.f.	32·5			Standby b.f.	5·9		
	Run No. 2 set on unit transformer		5	104			36	89			10·9	
	Run No. 3 set on unit transformer		0·85 p.f.				0·33 p.f.				0·85 p.f.	102
	No. 1, No. 2 or No. 3 standby b.f. comes in											
7	General services ..	5			General services ..	5			General services ..	5		
	Start No. 1 set ..	10	25	98	Start No. 1 set ..	10	49	84	Start No. 1 set ..	10	25	
	Start No. 2 set ..	10	0·85 p.f.		Start No. 2 set (without b.f.)	5	0·51 p.f.		Start No. 2 set ..	10	0·85 p.f.	98
					Start No. 2 b.f. ..	32·5						
8	General services ..	5			General Services ..	5			General services ..	5		
	Run No. 1 set on unit transformer				Start No. 2 set ..	10			Start No. 2 set ..	10		
	Start No. 2 set ..	10	25	98	Start No. 3 set ..	10	53·5		Start No. 3 set ..	10	30·9	
	Start No. 3 set ..	10	0·85 p.f.		No. 1 standby b.f. ..	32·5	0·54 p.f.	82	No. 1 standby b.f. ..	5·9	0·85 p.f.	95·5
	No. 1 set standby b.f. comes in											
9	General services ..	5			General services ..	5			General services ..	5		
	Start No. 1 set ..	10			Start No. 1 set ..	10			Start No. 1 set ..	10		
	Start No. 2 set ..	10	35	93·5	Start No. 2 set ..	10	58	80	Start No. 2 set ..	10	35	93·5
	Start No. 3 set ..	10	0·85 p.f.		Start No. 3 set (without b.f.)	5	0·57 p.f.		Start No. 3 set ..	10	0·85 p.f.	
					Start No. 3 b.f. ..	32·5						
10	General services ..	5	20	100	General services ..	5	20	100	General services ..	5	20	100
	Run No. 1 set on station transformer	15	0·85 p.f.		Run No. 1 set on station transformer	15	0·85 p.f.		Run No. 1 set on station transformer.	15	0·85 p.f.	
11	General services ..	5			General services ..	5			General services ..	5		
	Run No. 1 set on station transformer	15	30		Run No. 1 set on station transformer	15	53·5	82	Run No. 1 set on station transformer	15	30	96
	Start No. 2 set ..	10	0·85 p.f.	96	Start No. 2 set (without b.f.)	5	0·52 p.f.		Start No. 2 set ..	10	0·85 p.f.	
					Start No. 2 set b.f. ..	32·5						

[continued on next page

Table 3.—*continued*

	Conditions postulated	Normal loads MVA	Normal loads Total MVA	Normal loads % Volts	Boiler feed pump: motor-starting condition — Conditions postulated	MVA	Total MVA	% Volts	Steady load after starting b.f. — Conditions postulated	MVA	Total MVA	% Volts
12	General services ..	5			General services ..	5			General services ..	5		
	Run No. 1 set on station transformer	15		100	Run No. 1 set on station transformer	15		84	Run No. 1 set on station transformer	15		
	Run No. 2 set on unit transformer		20 0·85 p.f.		No. 2 standby b.f. ..	32·5	49 0·51 p.f.		No. 2 standby b.f. ..	5·9	25·9 0·85 p.f.	97·5
	No. 2 set standby b.f. comes in											
13	General services ..	5			General services ..	5			General services ..	5		
	Run No. 1 set on station transformer	15			Run No. 1 set on station transformer	15			Run No. 1 set on station transformer	15		
	Run No. 2 set on unit transformer		30 0·85 p.f.	96	Start No. 3 set ..	10	58 0·57 p.f.	80	Start No. 3 set ..	10	35·9 0·85 p.f.	93
	Start No. 3 set ..	10			No. 2 standby b.f. ..	32·5			No. 2 standby b.f. ..	5·9		
	No. 2 standby b.f. comes in											

Note 1. Loads are imposed on one station transformer, 22·5 MVA rating. Loads estimated at 6·6 kV
Note 2. The voltage drops are based on a no-load voltage of 7 kV on the station transformer and no tap-change.

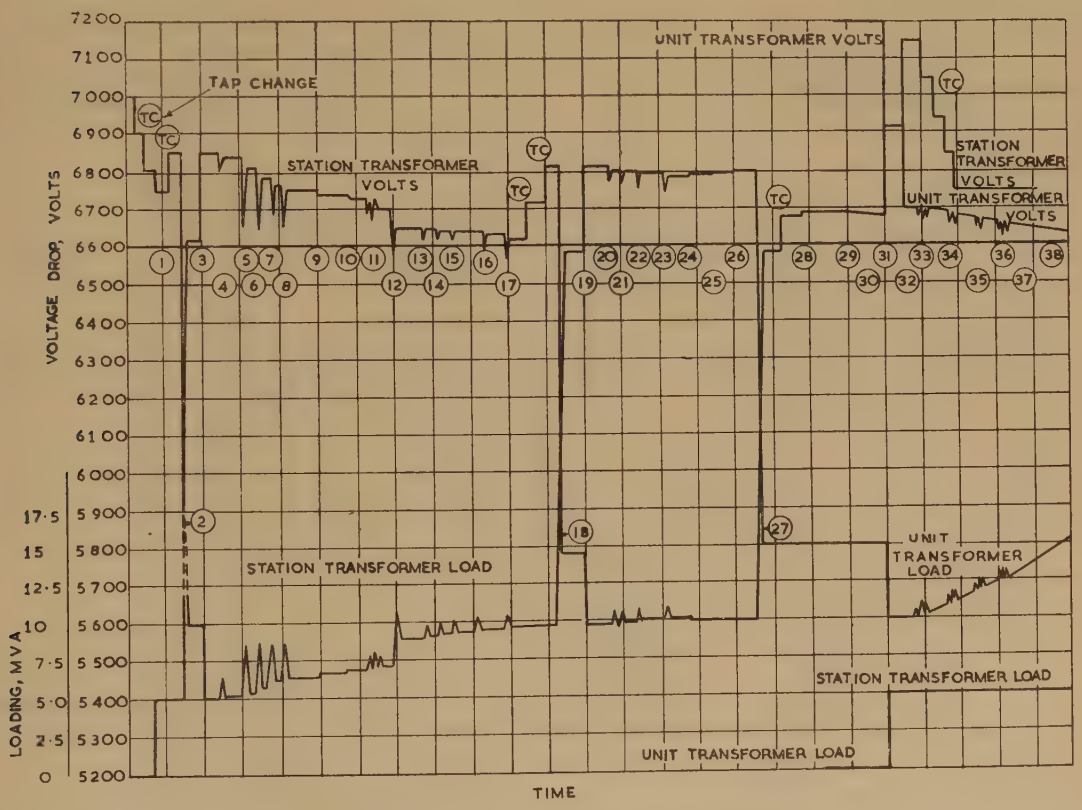


Fig. 3.—Design estimates for 200 MW unit cold start; voltage drop and loading diagram.

Time
(1) 0000 General services.
(2) 0000 Boiler feed pump.
(3) 0010 Boiler feed pump off.
(4) 0011 No 1 boiler circulating pump.
(5) 0012 I.D. fan 'A'.
(6) 0012½ I.D. fan 'B'.
(7) 0013 F.D. fan 'A'.
(8) 0013½ F.D. fan 'B'.
(9) 0015 Oil burners.
(10) 0100 Precipitators.
(11) 0100 No. 1 mill group (if coal used for starting).
(12) 0130 C.W. pump.
(13) 0200 Jacking pump.
(14) 0201 Turbine main oil pump (a.c.).
(15) 0202 Barring gear.
(16) 0203 No. 2 boiler circulating pump.
(17) 0255 No. 3 boiler circulating pump.
(18) 0256 Boiler-feed pump.

Time
(19) 0306 Boiler-feed pump off.
(20) 0307 Q.S. air pump.
(21) 0307½ No. 1 main air pump.
(22) 0308 No. 2 main air pump.
(23) 0309 Extraction pump.
(24) 0310 Jacking and barring off.
(25) 0311 Machine rolling on steam.
(26) 0312 Q.S. air pump off.
(27) 0330 Boiler-feed pump.
(28) 0429 Auxiliary oil off.
(29) 0430 Machine synchronized.
Machine loaded at 4 MW/min.
(31) 0500 Station and unit transformer paralleled.
(32) 0501 Station transformer off load.
(33), (36) Nos. 2–5 mill groups.
(37) Machine increasing load.
(38) Machine full load.

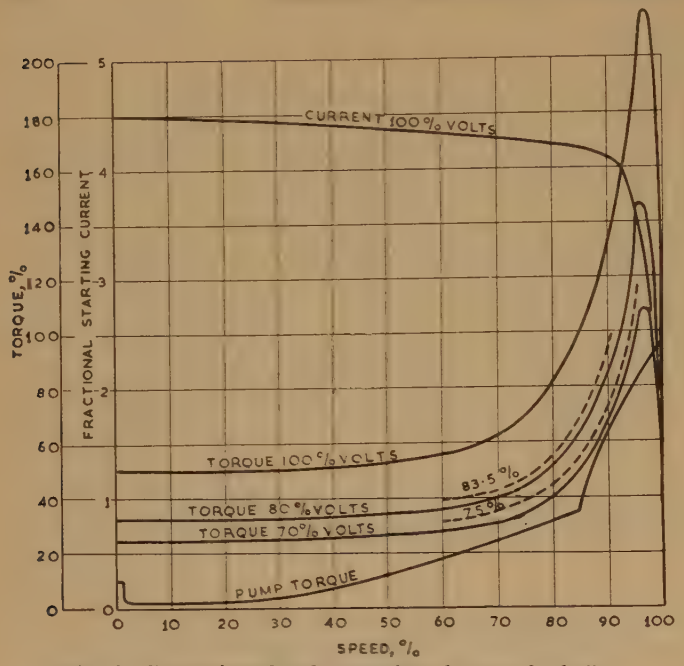


Fig. 4.—Torque/speed and current/speed curves for boiler feed-pump motors.

As regards the voltage drop, the figures are based on the normal tapping of the transformer, and the tap change could normally be used if any difficulty arose with low voltage.

(12) PARAMETERS OF SYSTEM DESIGN

The design of the distribution system requires the integration of a number of factors already discussed, namely choice of voltage, switchgear rating, loads, voltage regulation and economics.

As a basis for the design, the following points need to be borne in mind:

(*a*) The system should be as simple as possible. Complication makes the system less reliable in operation, especially in an emergency.

(*b*) As far as possible it is desirable to use standard equipment. Non-standard equipment is expensive and untried in service.

(*c*) Voltage drops due to the starting of motors should not be greater than 20% of rated voltage. It might be permissible to allow the voltage to fall slightly below 80% of the rating in special circumstances, but this requires careful consideration.

(*d*) For purposes of calculating the short-circuit level, two conditions of operation are considered: paralleling of one unit and one station transformer and paralleling of two station transformers.

To illustrate these various factors a station comprising five 200 MW units is considered below.

An examination of the loads shown in Table 3 indicates the choice of 6·6 kV as the voltage, with a station transformer of

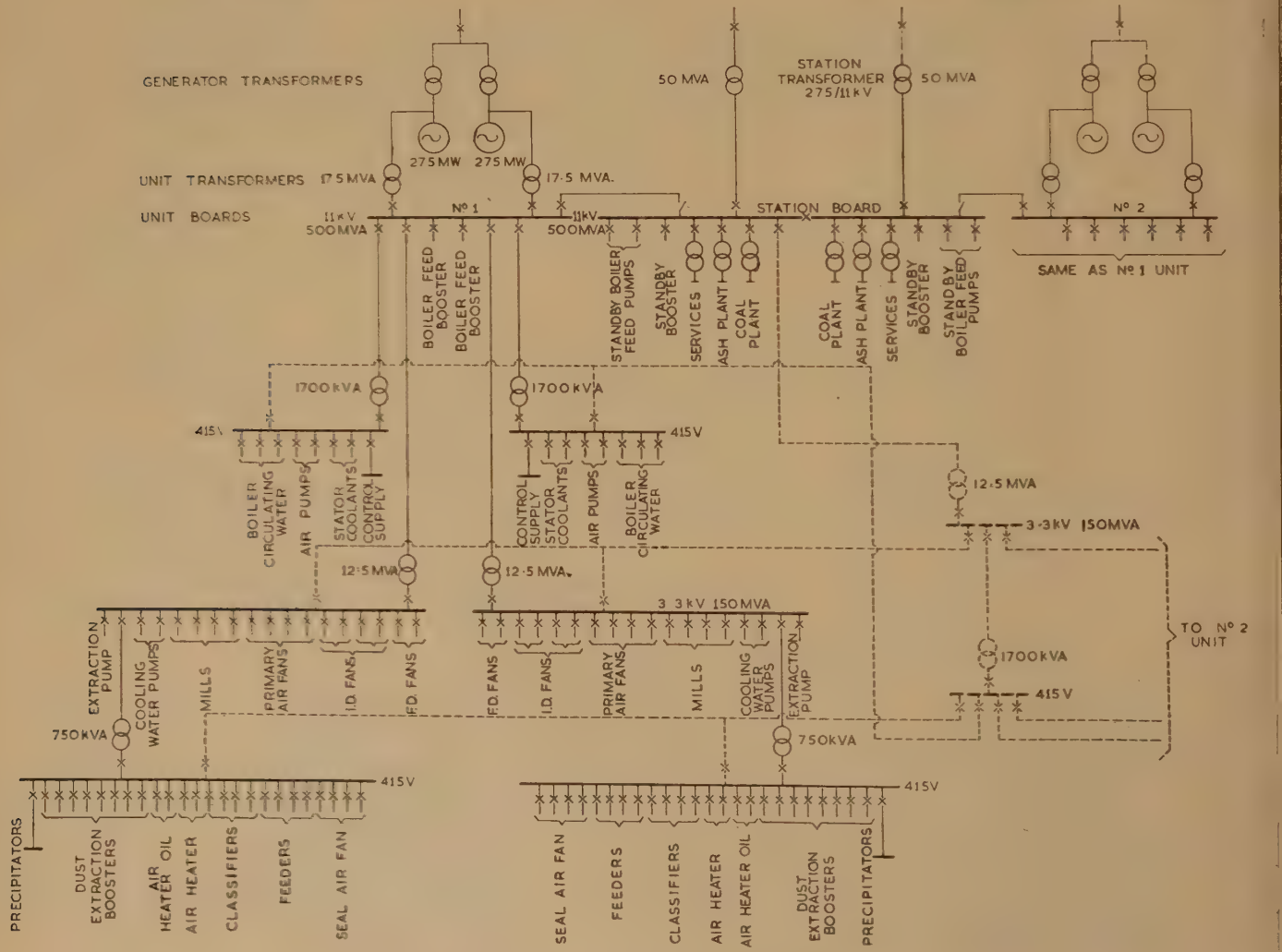


Fig. 5.—Auxiliary power connections: 2 × 550 MW units.

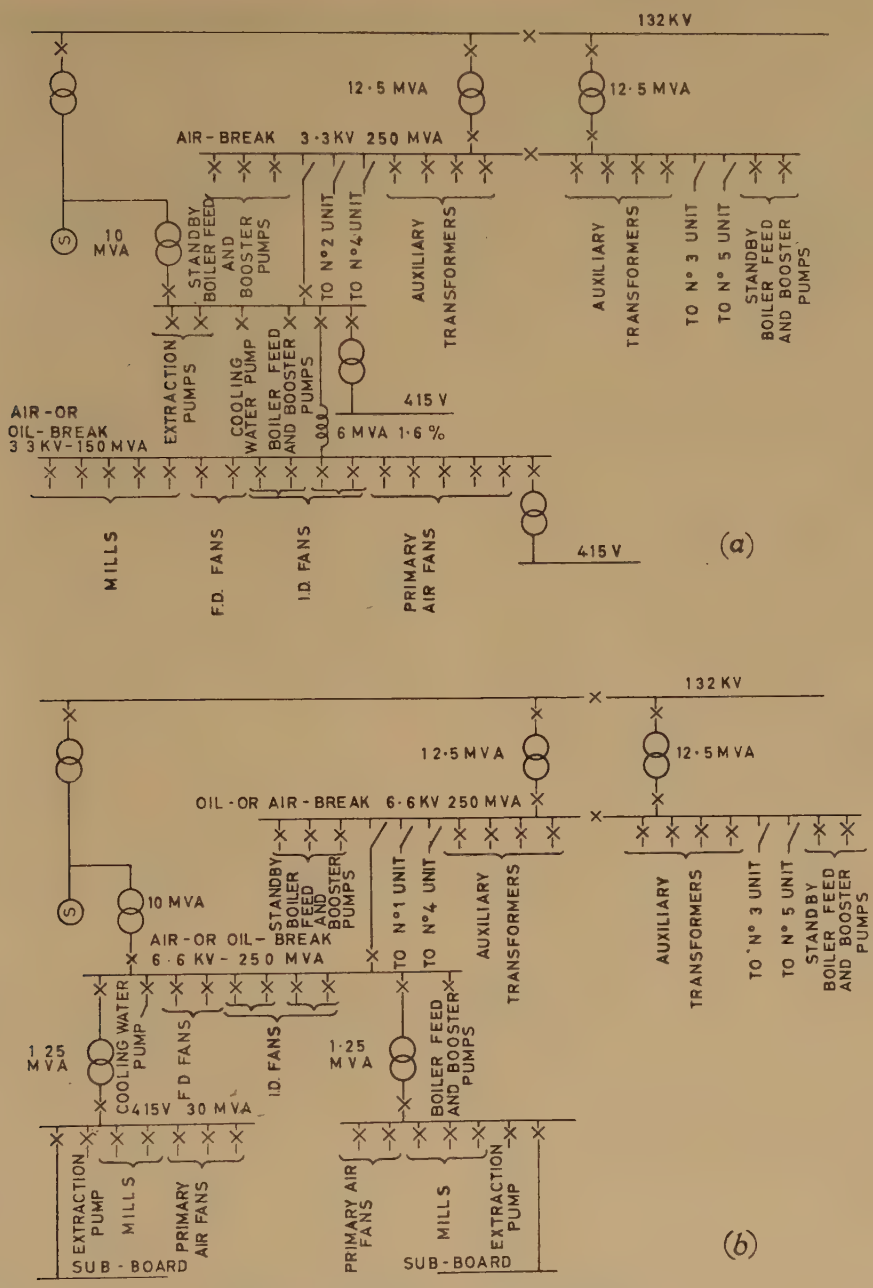


Fig. 6.—Connections for 5 × 120 MW station.

(*a*) Schemes 1 and 2, 3·3 kV.
(*b*) Schemes 3 and 4, 6·6 kV.

22·5 MVA: 11 kV is ruled out both on economic grounds and because of the possibility that motors at 6·6 kV might be more reliable than at 11 kV. At 3·3 kV the current would be excessive.

Considering the short-circuit rating of the 6·6 kV switchgear, 250, 350 and 500 MVA are available in standard ratings. 250 MVA is eliminated because of the large voltage drop caused by high-reactance transformers needed to keep the short-circuit level down to 250 MVA. 500 MVA is eliminated because of the high cost. (See Appendix 15.3 for costs.)

With 350 MVA switchgear it is necessary to introduce a reactor between the transformers in order to reduce the transformer reactance and at the same time limit the short-circuit level to 350 MVA.

The importance of reducing the transformer reactance, and hence the voltage drop, is illustrated in Fig. 4. This shows the starting characteristics of a typical boiler feed pump, where it will be noticed that the margin between the motor torque and pump torque is very small at 80% voltage. Low voltage has the effect of increasing the starting run-up time of the pump, and it is important to keep the run-up time as short as possible because of the time margin of the boiler drum capacity.

(13) FUTURE DEVELOPMENTS

As far as auxiliary power systems are concerned, power stations are likely to develop in the direction of larger conventional units and nuclear power.

As regards larger units, the main problem will be in dealing

with boiler feed pumps. Present designs indicate that the normal-running boiler feed pump will either be driven from the main shaft of the turbo-generator or separately steam driven, leaving only the standby to be dealt with by the electrical system. For units above 200 MW, 11 kV appears to be the most suitable voltage because of the large auxiliary loads. A scheme for a station comprising two 550 MW units is shown in Fig. 5.

As far as can be seen, nuclear stations will present no serious problem to the electrical system designer, except perhaps in giving adequate standby supplies to vital circuits. There may also be problems associated with the very large fans which circulate the coolant gas. The unit transformer principle has been applied for current designs.

(14) ACKNOWLEDGMENT

While the opinions expressed are those of the author, he would like to thank the Central Electricity Generating Board for permission to publish the paper.

(15) APPENDICES

(15.1) Cost Comparison: Shaft Generator and Unit Transformer

Capital Cost: Shaft Generator.

	£
Cost of 15 MW shaft generator complete with exciter	55 000
Extra for building and foundations	1 500
Less saving due to reduction in capacity of main generator	25 000
Total capital cost of shaft generator scheme	31 500

Capital Cost: Unit Transformer.

Cost of 17·5 MVA transformer 16·5/11 kV 16 000

Difference in Capital Cost £15 500

Losses.

Assume 60% load factor and 0·5d per unit

Losses = kW × hours in year × load factor × unit cost × efficiency loss

= 15 000 × 8 760 × 0·6 × 0·5/240 × efficiency loss

= 164 500 × efficiency loss

	£ per annum
Saving on main generator, 164 500 × 0·015	2470
Loss on shaft generator, 164 500 × 0·035	5 760
Total loss, 5 760 — 2470	3 290
Loss on unit transformer, 164 500 × 0·01	1 645
Difference in losses	1 645

Overall Saving.

In favour of unit transformer scheme	£
Capital saving	15 500
Saving due to losses	1 645 per annum

(15.2) Cost Comparison for a 5 × 120 MW Station

	3·3 kV		6·6 kV	
	Scheme 1 3·3 kV 250 MVA 3·3 kV 150 MVA Air-break gear 415 V 30 MVA	Scheme 2 3·3 kV 250 MVA Air-break gear 3·3 kV 150 MVA Oil-break gear 415 V 30 MVA	Scheme 3 6·6 kV 250 MVA Air-break gear 415 V 30 MVA	Scheme 4 6·6 kV 250 MVA Oil-break gear 415 V 30 MVA
	£ thousands	£ thousands	£ thousands	£ thousands
Switchgear	260	230	200	145
Transformers	129	129	158	158
Cables	50	50	40	40
Motors	340	340	365	365
Fire-fighting	—	8	—	10
Reactors	5	5	—	—
Total capital	784	762	763	718
Losses	10	10	50	50
Total, capital + losses	794	772	813	768
Difference	+26	+4	+45	Datum
Percentage difference	+3·38	+0·52	+5·85	—

(15.3) Cost Comparison for a 5 × 200 MW Station

	Scheme 1 6·6 kV 350 MVA 415 V 15 and 30 MVA	Scheme 2 6·6 kV 350 MVA 3·3 kV 150 MVA 415 V 15 and 30 MVA	Scheme 3 11 kV 350 MVA 415 V 15 and 30 MVA	Scheme 4 6·6 kV 500 MVA 415 V 15 and 30 MVA	Scheme 5 11 kV 500 MVA 415 V 15 and 30 MVA
	£ thousands	£ thousands	£ thousands	£ thousands	£ thousands
Switchgear	448	458	368	600	470
Transformers	284	300	284	284	284
Motors	1001	1060	1123	1001	1123
Cables	119	107	88	119	88
Total	1852	1925	1863	2004	1965
Difference	Datum	+73	+11	+152	+113
Percentage difference	—	+3·9	+0·6	+8·2	+6

DISCUSSION BEFORE THE SUPPLY SECTION, 22ND APRIL, 1959

Professor R. O. Kapp: The term 'auxiliaries' might convey to the uninitiated the notion that they are a relatively unimportant part of a power station, and since they consume at most only 7% of the station output, this false impression might be confirmed. The extent of its falsity is realized when one examines on a layout drawing the floor space occupied by auxiliaries, considers the amount of attention that has to be given by the designer to their choice and planning, or remembers that they provide the majority of problems of operation and maintenance.

The care taken to keep the consumption of auxiliary plant low reflects the meticulous attention given to economics in the electricity supply industry. When a station engineer is concerned with his costs per kilowatt-hour, he is hardly interested in the first or second, or even perhaps the third, significant figure of that cost. He knows it already without looking up the records. He is interested in that small fraction of 1% by which the costs can vary with controllable conditions.

Electricity costing has become such a fine art in comparison with other industries because electricity is a comparatively simple commodity; furthermore, for more than 60 years some of the best engineering minds in electricity supply have been given to problems of cost accounting. There was a time when The Institution had a paper nearly every year on this subject and we are now reaping the benefit of this work. It is the addition of many small fractions of 1%, painstakingly saved, that has caused the cost of electricity to be reduced steadily relative to that of other commodities.

I welcome the author's advocacy of the station-transformer scheme. When one is seeking small economies one must consider carefully the size of the station transformers, and remember that the capital cost of excess transformer capacity is not the whole, or even the largest part, of its cost. The largest part is the capitalized cost of the iron losses, which occur at 100% load factor.

In a power station with five 200 MW units, the rating of the station transformers is determined by the number of sets that have to be started simultaneously. The unit transformer is not energized during starting and so the auxiliaries for that set must be supplied by the station transformer; in the interest of small economies it is therefore necessary to consider how many sets need to be started simultaneously. The rate at which the station is going to be extended to its full capacity may determine the number of station transformers, and with 200 MW sets the interval between commissionings is likely to be rather long. But one needs a station transformer and a standby for the very first set; if these two suffice for the ultimate size of the station, this may provide a wasteful excess capacity until the time comes to start up two sets simultaneously. So it would seem worth considering whether, instead of having two station transformers with 100% standby, it would not be better to have three station transformers, with 50% standby, of which two only would be installed initially.

The requisite amount of standby auxiliary plant depends on the reliability of the items in question. Records covering only those failures that result in curtailment of supply are no measure of this reliability. Additional information about failures that do not result in curtailment is needed and would make it possible to assess the optimum standby capacity more accurately than can be done to-day.

Lastly, I should like to ask about the method of using station transformers that seems to be developing in the United States, called 'quick switching'. Its purpose is to save rupturing capacity of switchgear, which it does by switching one board off before switching the other one on. This strikes an old-fashioned engineer like myself as a terribly crude method. However, if it is done, it must work. What does the author think about the method? So far as I know, it has hitherto been employed in this country in oil refineries only.

Mr. C. Bottrell: The paper is really only concerned with coal-fired stations. There is no reference to oil firing and only the most cursory reference to nuclear power stations.

The information on station loads is extremely useful, and when taken as a supplement to that contained in the paper by Kennedy and Hutchinson,* is a valuable addition to the information we have on auxiliary loadings, of which there is insufficient published. It is, of course, of great assistance to station designers.

In Section 5 reference is made to the need for ensuring that circulating currents are kept within the operating limits of the transformer circuits when sections of the Grid are paralleled to the low-voltage switchgear. It would be useful if the author could give some indication of the order of phase-angle one might get across sections of the low-voltage switchgear in practice in certain installations.

Regarding the arrangements for supplies to extraction pumps, there might be a good case for an automatic feature for the change-over of the extraction pumps in the event of failure of the main pump.

The author refers to the provision of a standby Diesel-alternator for giving an alternative supply to the a.c. flushing pump and seal-oil pump. Surely two sets would be required in practice, one to cover the other in the event of breakdown?

One important difference in the conditions for nuclear stations is that we have not reached the stage where a strictly unit supply scheme could be adopted. Due to various limitations, the number of boilers in relation to the reactor and the number of turbines is somewhat different. We have a multiplicity of boilers and turbines for a single reactor.

There are two very good reasons why the supplies at a nuclear station should be even more reliable than the more conventional station supply. One is the consideration of safety from the aspect of nuclear hazards. The other is the fact that once the reactor has been tripped out, it takes many hours longer to get back into service than a normal conventional station.

Mr. W. N. Waggott: During the past 40 years I have specified the unit-transformer scheme for more than 50 generating stations. It is applicable to generators of any rating. The association of a generator with a boiler as a unit is ideally served by the scheme, and its use in modern stations is the logical continuance of proven practice.

The variation in Fig. 2(*a*) is incomplete. The boards should be interconnected, thus providing standby supplies. This scheme is attractive for stations with machines of medium rating and switching at high voltage, with the cost of providing station transformer circuits unduly high. It was first applied by me over 30 years ago, and has been used recently in a station containing four 30 MW generators with 132 kV switching.

The voltage for large motors has occasioned much debate: for 60 MW generators, 3·3 kV has sufficed, while for 120 MW generators I favour 6·6 kV. For 200 MW generators and above I recommend three supply voltages, namely 415 volts for small motors, 3·3 kV for medium motors and 11 kV for large motors. Motor windings and terminal arrangements must be robust. This places a lower limit on the rating for any voltage. Some of the recent breakdowns in 3·3 kV motors in generating stations might be associated with failure to observe this requirement.

* KENNEDY, G. F., and HUTCHINSON, F. J.: 'Power Station Auxiliary Plant' *Proceedings of The Institution of Mechanical Engineers*, 1956, 170, p. 341.

Experience indicates the necessity for substantial d.c. supplies for a period longer than batteries could cover. A number of modern stations have been equipped with Diesel-driven d.c. generators for emergency duties.

When planning auxiliary supplies, there should be close collaboration between mechanical and electrical interests. The rating of electrically-driven auxiliaries must be kept within bounds. Steam drive, preferably from the main turbine through a fluid coupling, is advisable for the normally running feed pump. Electrically-driven feed pumps should not exceed half rating.

Mr. F. J. Hutchinson: The arrangement and design of main and secondary auxiliary cables becomes very important as auxiliary powers and voltages continue to increase.

Several motor terminal-box explosions have occurred recently which originated as phase or earth faults, probably due to dampness resulting from repeated condensation. Explosions occurred because the terminal boxes had not been designed on a rupturing-capacity basis.

Low currents which result from high voltages for comparatively small motors produce cables of small cross-section when design is based on purely thermal considerations. These cables have very low heat inertia under transient conditions and burn out much more rapidly than cables designed for the rupturing power which is released under fault conditions.

A suggested design time-grading of rupturing power from the switchgear through the cable to the motor is as follows:

System voltage	3·3 kV, 6·6 kV
Design rupturing capacity	150 MVA, 350 MVA
	sec
Busbars, including top connections	3
Switch cable box and cable ..	$\frac{1}{2}$
Motor terminal box	$\frac{1}{4}$

Motor terminal boxes for 3·3 kV and higher voltages must also be designed to withstand the energy released under short-circuit conditions. Furthermore, to avoid repeated condensation they should be air-tight on the motor end-connections side, on the cable tails-entry side, and from the front where the cover is detachable for access. Barriers should be provided between studs or other phase connections.

Mr. A. Abbott: I think the title of the paper should have been 'Electrical Supplies to Auxiliaries in Power Stations with Large Machines'.

Whilst 200 MW machines and above may become standard in this country, smaller sets will still be supplied abroad. Hence some views expressed in the paper could be misleading. Cannot the scheme shown in Fig. 2 be applied to larger machines? Staff who have served at Meaford inform me that this scheme is simpler to operate than others used in this country.

The most reliable supply of electricity at power stations connected to the Grid is from the Grid. Alternatively, for standby purposes a lower voltage supply from the local Area Board could be installed, as at Meaford.

The generator switch could take the form of a remote-operated low-load making isolator of adequate current-carrying capacity and mechanical robustness.

Applying this scheme to Fig. 2(*b*), the omission of four 132/3·3 kV station transformers, two 132 kV Grid switching bays and interconnecting cable, 3·3 kV station and starting boards, plus the saving in civil costs at the station and Grid substation would yield about £500 000.

Referring to switchgear, about 40% of the total cost of a modern power station is for civil works. If 0·03–0·05% represents the capital cost of the 3·3 kV auxiliary switchgear, it is sensible to install air-break switchgear at a wider cost differential compared with oil-break, even though it saves only 0·5% of the overall civil costs, remembering that fire-segregation walls, oil soakaways and special fire-fighting equipment are not required with air-break switchgear.

Finally, the auxiliary load for a station as shown in Fig. 1 represents the peak load of a moderate sized town, except that it is contained in a building about 400 yd × 30 yd.

It might be a good thing if the advice of distribution engineers was sought in the early design stage.

Mr. F. H. E. Myers: The author mentions that operational statistics of plant already in service can be a useful guide in assessing loads. I have analysed the statistical returns for the stations of the Central Electricity Generating Board for the year ending 1st April, 1957, and have found that the auxiliary power is about 4% for the smaller stoker-fired stations, and about 6–7% for the larger pulverized-fuel-fired stations, depending on the loading programme. Some stations with unusual operating conditions have higher consumption of auxiliary power.

Fig. A shows two curves which represent the mean of a large number of points obtained by plotting auxiliary power against

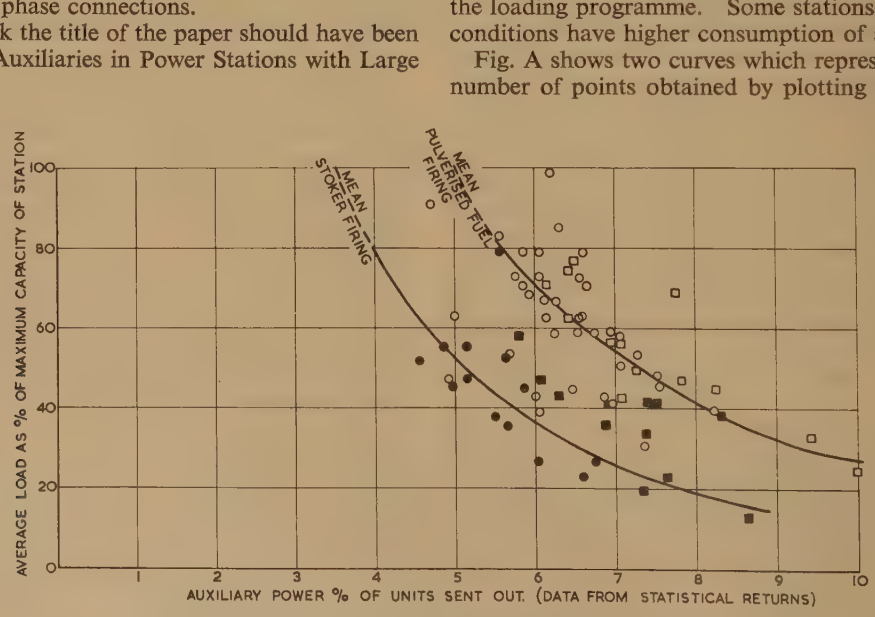


Fig. A.—Auxiliary power percentage versus average load.

● River or sea-water cooling
■ Cooling towers
} Stations with stoker firing.

○ River or sea-water cooling
□ Cooling towers
} Stations with pulverized-fuel firing.

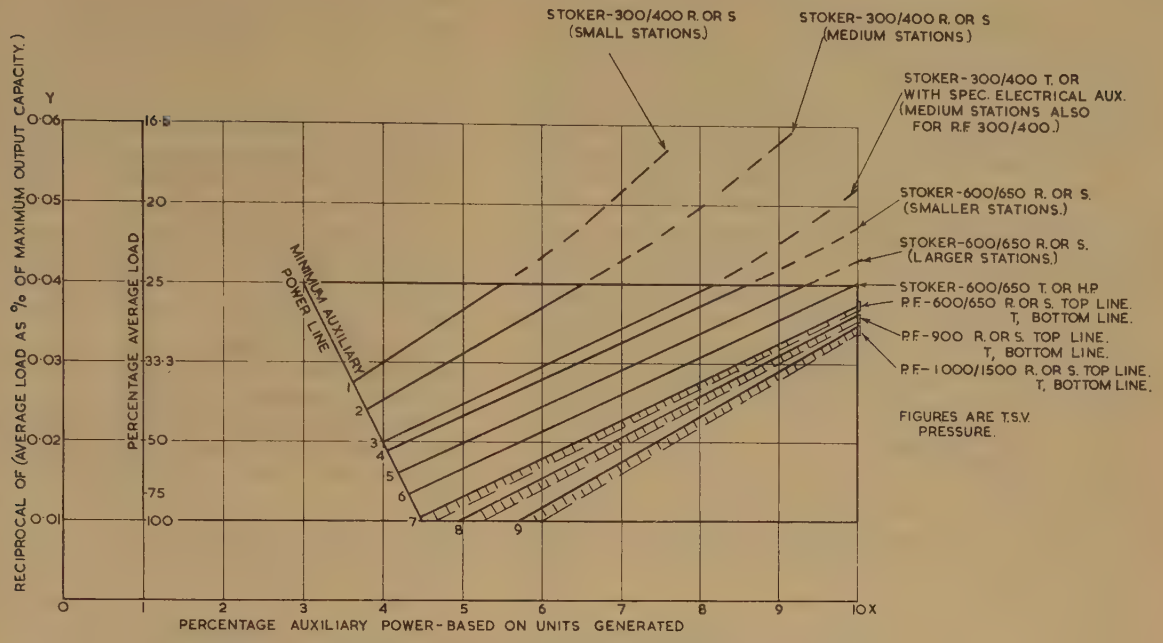


Fig. B.—Auxiliary power characteristics for non-reheat coal-fired power stations.

R = River-water cooling.
S = Sea-water cooling.
T = Cooling towers.

average load taken as a fraction of maximum possible output. As these curves tend to assume hyperbolic shape over the working range, several other charts were plotted separating out the types and sizes of station.

Fig. B is a summary chart which illustrates a first-approximation straight-line law between auxiliary power consumption and the reciprocal of the average load, for different sizes of stoker-fired and pulverized-fuel-fired power stations.

From test data, and from known parameters of plant, I have calculated the auxiliary power for a 200 MW unit to be 6·75%, assuming 100% plant utilization. The paper mentions 15·5 MVA, i.e. about 13·5 MW when allowance is made for the power factor of the various motors, and this is 6·75% of 200 MW. If the plant is operated at a mean load of 90% of its maximum possible output, then the auxiliary power will be about 7·5%, i.e. 6·75 divided by 0·9 according to the 'reciprocal law'.

It ought to be explained that this figure of 7·5% applies to a non-reheat plant. For single reheat, it is found that the gain in output is, say, 6% for the same feedwater pumping power, and this would therefore reduce the auxiliary power when expressed as a percentage of total output, so that it is likely that the figure of 7% will be attained.

Fig. B affords an explanation of the author's statement that the electrical load required for running a station is of the order of 4% to 7% of the station output, when considering the diverse types and sizes of stations.

In Table 1, the estimated figure for power required by the milling plant and exhauster, which works out at about 27 kWh/ton of coal, seems a little high. I have found the mean value for this type of plant to be 23 kWh/ton, while the mills using primary air fans take about 18 or 19 kWh/ton. Tube mills take 30–35 kWh/ton.

In Table 2, the estimated power for coal and ash handling works out at about 3·4 and 4·6 kWh/ton of coal, whereas I have had figures of 1–2 kWh/ton with about 500 ft of conveyor.

It is interesting to see how close the economic comparison is between 6·6 and 11 kV switchgear (schemes 1 and 3 of Section 15.3). I believe air-blast 11 kV switchgear is available, and I would like to know whether this has been considered, as it seems to have the advantage of simplicity and reliability, and is not subject to fire-risk attributable to oil-break gear.

The author mentioned the use of contactor-type gear for motors up to 100 h.p. Are these restricted to 'service' motors, because it seems to me that air-break switchgear should be used for the urgent auxiliaries of small rating at low and medium voltage. Contactor gear would be suitable for sequence-control interlocking for such items as conveyor drives.

It is mentioned that it may be permissible for the voltage to drop to 80% of its normal value in special circumstances. Does this mean that the motors are automatically switched off if the voltage falls below this value? If so, is thought to be given to auto-reclose features associated with time lag to overcome temporary voltage depression or transient fault conditions to improve continuity of supply to urgent auxiliaries?

Mr. S. A. Clarke: The fundamental principle of the unit transformer scheme is that there can be no half-measures: one either adopts the principle rigidly or not at all. It is no good trying to cheat oneself into believing one has a unit scheme if interconnections are added later. Those who are not engaged in station design may fail to appreciate the temptation to do so. It is brought about by the present rapidly increasing size of sets after an initial post-war pause at 60 MW. The electrical auxiliary system is designed at a very early stage of the programme, so that, if it is decided later to change the size of sets, reinforcement of the auxiliary system often becomes necessary and interconnection offers a solution so long as the short-circuit capacity of the switchgear is not exceeded.

A variation of the starting board scheme in Fig. 2(*b*) has recently been used in a station in the London Region. If double busbars are used or a bus cable is put between the starting and running boards in Fig. 2(*b*), the transformer arrangement becomes more flexible. The extra cost of double-busbar switchgear must, however, be set against the greater flexibility. The

disadvantage of the scheme shown in Fig. 2(*b*) is that two of the station transformers are not used except at starting.

Prof. Kapp suggested that some consideration should be given to the question of iron losses by reducing the standby capacity of the station transformers. If all the transformers can be used for starting and running, the problem is simplified.

I would support Mr. Abbot in making use of Area Board supplies. These are required during construction and, with care, can be incorporated into the final design.

Are the prices of switchgear given in Schedule 15.3 based on air or oil break? It would be useful to have figures corresponding to those for the specified type of switchgear in Schedule 15.2.

Mr. J. E. Stubbs: The recent change in this problem has been one of scale brought about by the increase in size of the generating units. The fundamental switchgear problem is not new; it is still how to handle economically the heavy load and short-circuit currents involved. The solutions are increase in switching voltage and sectionalization.

Until recently, 3·3 kV has been adequate for primary distribution, but now 6·6 kV, and even 11 kV, are necessary. At 11 kV, however, the minimum economical motor size is around 1 000 h.p. so that double transformation is required, with an intermediate voltage of 3·3 kV.

Sectionalization is inherent with unit transformers where each generator independently supplies its own essential auxiliaries. As the transformer size increases there is the possibility of carrying sectionalization a stage further by providing two secondary windings, each of half rating. These then feed independent unit boards with the auxiliaries distributed between them. Boiler feed is provided by two pumps, one on each board. The standby is 50%, as distinct from 100%, obtained from a third unit on the station board, arranged to replace automatically either normal pump in emergency. Duplicate unit boards can reduce fault-level and eliminate heavy-current interconnectors. For circuits above 2 kA, two circuit-breaker equipments of half-rating may still be cheaper than one for full-load; cables have to be run in parallel in either case.

For the station transformers, such a division of secondary windings is economically impracticable at the high primary voltages contemplated.

An alternative scheme of off-load change-over between station and unit supplies has been used oversea. This has the advantages of reducing fault-level and avoiding the necessity of synchronizing before change-over, but at the expense of switching surges in the motor circuits.

Mr. D. J. Miller: The author makes no reference to protective gear. I hope that does not mean he considers auxiliaries would be better without it. It is an important aspect which should be borne in mind throughout the design of the scheme.

With higher-voltage auxiliary systems of up to 11 kV, does the author think that a resistance system of earthing is warranted? The advantage of earthing through a resistance would be that damage to costly motors would be minimized in the event of an internal fault. It would also reduce stray voltages due to faults in the station, which can constitute a hazard. Will the author also comment on the use of under-voltage releases on auxiliary motors and the settings and time delays which he considers suitable?

A controversial question, particularly for smaller stations where all the auxiliaries are on 415 volts, is the use of standby earth-leakage protection in the transformer neutral. This is important in these smaller stations because, in the event of a failure of the protective gear on a far from essential auxiliary, the standby earth-leakage can trip all the station auxiliaries. On the other hand, standby earth-leakage protection in the transformer neutral is probably the only effective method of detecting earth faults on 415-volt systems where the earth-fault current is restricted by the fault impedance.

There has been much discussion on centralization of control in recent years, and I should like to have the author's opinions on control.

Mr. J. C. Bradbury-Williams: I feel that in the design of the auxiliary system consideration should be given to power supplies for construction and commissioning. Even in Britain with a Grid system it can happen that on a new site the Grid station cannot be completed at an appropriate stage of the construction programme. What arrangements would the author make for these supplies? At oversea stations there is often no Grid system. Commissioning supplies are difficult and even cold starting requires special arrangements.

Regarding under-voltage protection, are latched-in starters recommended for essential auxiliaries?

The selection of voltage for the variable-speed drives is not easy, particularly where the range of speed is above and below normal running speed. The author's views on the selection of the proper voltage for motors where the speed range is considerable would be helpful.

The paper discusses auxiliaries of coal-fired stations. Although Britain has only a 15 MW unit gas-turbine set, Switzerland has a 27 MW set, and it would be interesting, for comparison, to have details of the auxiliary system of this type of plant, including the auxiliary load. I hope the rather large compressor shaft horse-power will be expressed in terms of equivalent electrical rating.

Some large sets are being built as two-line machines. Would the author recommend a unit transformer for each of the generators of the two lines, for only one of the lines, or a common transformer?

Mr. C. J. O. Garrard: I should like to make a point concerning the remarks of Mr. Abbott and Mr. Waggott about unit transformer schemes using Method A.

I should not have thought difficulties in providing switchgear for the generator output would have been a limiting factor. One has 4 kA metalclad units in operation quite satisfactorily, and it would not be very difficult to design a 6 kA unit if care were taken to keep magnetic material away from the immediate neighbourhood of the conductors.

Mr. T. Molyneaux: I would like to comment from the mechanical engineer's point of view.

One complication with a feed-pump system of two 100% pumps, one on the unit and one on the station board, is that the unit pump is doing all the work.

Ways out of this difficulty are to have change-over switchgear or means of changing over cables, but for the modern plant there is another method. Nearly all modern high-pressure pumps are of the barrel-casing type, and the internals are interchangeable. They can be taken from one feed pump and put in the other.

Another factor is size. The C.E.G.B. have generally called for two 100% pumps, but this is not necessarily the right answer. Feed pumps are fairly reliable pieces of equipment to-day, and there is a very good case for not having them as standby equipment. There are several stations to-day which do not have 100% standby plant. They have one 100%, two 50% or sometimes three 50% pumps. A great saving is possible on station and unit transformer sizes with this arrangement. As the feed pump is the main item of auxiliary equipment in a modern plant, there is a very good case for reducing its size.

The author states that battery supplies will be required for emergency lighting, standby oil-flushing and seal-oil pumps, and turbine governor motor. I think there is a good case in modern high-temperature plant for adding barring gear since it is difficult

to crash shut-down without it. It is doubtful if it would be possible to start the turbine again for a long time—in fact permanent damage may be done to the machine by not having barring gear available at all times.

Mr. D. J. E. Evans (*communicated*): During the discussion several speakers referred to the quick switching of induction motors. This method has been used on the Continent,* in the United States† and at oil refineries in this country. It is also proposed for the Hunterston nuclear generating station.

When the supply to an induction motor is removed, the magnetic field does not die away instantaneously. The fluxes in each of the rotor windings tend to decrease, but as the rotor windings are short-circuited, e.m.f.'s are induced and set up currents tending to maintain these fluxes. The resultant flux rotates at rotor speed relative to the stator and not at synchronous speed as it did before the supply was switched off. Not only does the magnitude of the residual busbar voltage decrease but its phase varies relative to the supply voltage.

Four methods of quick switching are possible:

(*a*) In the 'fast' quick-switching scheme the incoming supply is reconnected in the shortest possible time, irrespective of the value of the residual voltage. Transient currents of some 12–15 times (with one case of 19 times) normal have been reported.

(*b*) The second method introduces a fixed time-delay before connecting the incoming supply. The residual busbar voltage is a function of the number of motors on the bars, their characteristics and the load. A delay that would be suitable for one set of load conditions might well not allow the residual voltage to decay sufficiently for another set of conditions.

(*c*) The third method differs from the fixed time-delay scheme in that the reconnection of the supply is delayed until the residual voltage has decayed to a known low value, usually some 20–25% of motor rated voltage. This method reduces the electrical and mechanical transients imposed on the induction motors.

(*d*) In the first three schemes the incoming standby supply is never connected in parallel with the normal supply during quick switching. These open-circuit methods of transfer become more difficult as the size of the generator increases. A continuous-circuit form of transfer has recently been described,* and is to be installed in the United States. In this, the incoming supply is connected in parallel with the normal supply for some two cycles during the transfer.

An analytical study of quick-switching schemes is complex, and extensive computer studies have been undertaken in the United States, with tests on actual installations.

NORTH-WESTERN CENTRE, AT MANCHESTER, 5TH MAY, 1959

Mr. C. W. Priest: Reliability becomes of enormous importance in the assessment of alternatives for auxiliary supply when the outage of a single 200 MW unit may cost the Board from £150 to £200 per hour in running low-merit plant. This figure must be remembered in assessing the economics of any system. Quite obviously the exceptionally large unit of to-day will probably be the standard unit of to-morrow, and the three-voltage system has a lot to commend it with the very high-capacity motors now having to be installed. Whether 11 kV is the right voltage for the highest system must be decided on individual circumstances, which vary widely.

The author mentioned fire risk with oil switchgear. Have there been any instances in recent years of modern properly rated equipment causing oil fires?

As regards emergency supplies, the batteries necessary for emergency operation are getting too large, and batteries of about 1-hour capacity, backed by a Diesel-driven a.c. generator, with rectifiers where necessary, might provide an even better service in emergency than auxiliaries alone.

I would prefer to see the barring-gear motors put on the emergency supplies. There is a risk of some distortion in the shaft when a restart is required in five or six hours if barring motors are not in operation.

Mr. C. Ayers: For any given project it is possible to sketch seven or eight auxiliary systems in a very short time. The difficult part of the exercise arises in endeavouring to determine the best system for the particular application.

The author mentions the work of Szwander on auxiliary systems. This work was done in 1947, since when units have increased in output from 60 to 550 MW and the boiler feed-pump from 800 to 6 000 h.p. Thus, 12 years of progress has increased unit and auxiliary capacities by a factor of almost 10.

However, I would suggest that the general—what may be termed conventional—approach to auxiliary system design is adequate for units up to 120 MW. Above this size and for nuclear stations I feel that a new approach is necessary and would put forward the following suggestions:

(*a*) The placing of the boiler feed-pumps or gas circulators in the nuclear station on a separate system. This would reduce the normal auxiliary system substantially, resulting in savings in switchgear and transformer costs. The separate system for the large auxiliaries could either be electrical or take the form of mechanical drives by turbines, etc. Such a solution may ease the problem of speed control, which has advantages for large feed pumps.

(*b*) The use of quick-switching technique as currently used on oil refineries and in America. By this means switchgear duty is reduced at the expense of a somewhat more onerous duty on the various auxiliary motors.

On the development of switchgear, I suggest that the use of Continental and North American voltages would ease the manufacturer's burden in that one range of switchgear would suit both the home and export markets.

Mr. H. Cahm: The location of the equipment in the power station is very closely linked with the economics of the choice of equipment. Many of the advantages of one or other of the schemes available can be nullified by factors such as the increased cost of cabling, etc.

In the stations with which I have been concerned, the auxiliary switchboards operating at 3·3 and 6·6 kV have been located in almost every conceivable position—both sides of the turbine house, above operating floor level, in the basement and between the basement and the operating floor level. Which position does the author consider to have the most advantages?

Mr. J. Tozer: The author rightly states that simplicity tends to increase reliability, and I should like to emphasize that good layout, enabling ease of erection and maintenance, is another contribution to reliability.

The unit principle described is true for the steam and feed systems in that there is no interconnection, but strictly speaking this is not so for the electrical systems described in the paper, where there are interconnections and alternative supplies.

The author describes the starting-up of a unit in respect of electrical supplies. I would emphasize the importance of ensuring that the station board supply is disconnected from the unit

* HUSKIN, A., MEAN, E., and DIENNE, C.: 'Selective Protection of Power Station Auxiliary Services, their Automatic Reclosure and that of Radial H.V. Lines', C.I.G.R.É., 1956, 3, Paper 304.

† BROWN, P. G., HEAGERTY, J. J., LEWIS, D. G., and SMITH, E. M. 'Switchgear with Stored-Energy Mechanism Applied to Steam-Station Auxiliary Transfer Arrangements', *Transactions of the American I.E.E.*, 1958, 77, Part III, p. 310.

* GRIFFIN, H.: 'Automatic Transfer of Control Station Auxiliary Motor Supply', Eleventh Annual Conference of Protective Relay Engineers, Agricultural and Mechanical College of Texas, 1958.

board before the generator is loaded, for it will probably be greatly overloaded if the two boards are left in parallel.

It might be considered that the author's use of barring gear as an example between urgent and service auxiliaries is rather unfortunate. While it is true that no permanent damage would be done to a machine should barring gear not be available after a shut-down, the remedial measures necessary would result in a temporary loss of availability.

I suggest that much greater emphasis should be given to the importance of reliable supplies to the electrostatic precipitators, bearing in mind our responsibilities to the community in relation to clean air.

High-pressure-oil jacking pumps are usually installed to avoid possible damage to the turbo-generator bearings when starting from rest. The reduction in starting torque on the barring motors is merely consequential.

Alarm systems now normally operate at 50 volts, using telephone-type equipment. Table 2 allows 200 kVA for the lighting and heating load for a 1 000 MW station, which seems to be extremely low.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. D. A. Dewison (*in reply*): A number of questions have been raised which could only be dealt with adequately by a full-length paper. Some points have been mentioned by more than one speaker, and these will be dealt with before replying to individual questions.

Quick Switching.—The technique of quick switching has been given considerable attention, but has not been adopted for power stations in this country. The method strikes Professor Kapp as being terribly crude, and I would agree that there are too many unknown factors involved for the scheme to be adopted with complete confidence. It is doubtful whether there is any economic advantage to be gained, because careful attention has to be given to voltage regulation which might result in either low-reactance transformers associated with high-rated switchgear, or costly segregation of circuits to keep load transfers to a satisfactory level.

On the unit system, there is little advantage to be gained by quick switching to maintain supplies, i.e. by providing automatic standby. This is because those faults which would cause a failure of the normal supply would usually require a unit shut-down, as, for example, with a fault on the unit transformer, since there is no point in keeping the generator running to feed into a fault.

The method has been used in the United States, but opinion there appears to be divided as to its merit. As described by Mr. Evans, there are several ways in which quick switching can be achieved, and even the advocates of the technique are by no means unanimous on which way is the best. It is not without significance that in one of the largest and newest of the stations in the United States the method has been abandoned.

The Meaford System [*Fig.* 2(*a*)].—It is agreed that the elimination of the station transformers, which this scheme allows, is economically attractive.

There is, however, considerable reluctance to introduce a circuit-breaker, or even an isolator, into the busbars connecting the generator with the generator transformer. This is undoubtedly due to the feeling that the reliability of the unit is thereby reduced, particularly where we are dealing with large units with heavy current ratings. This, coupled with the other factors mentioned in the paper, probably explains why the scheme has not met with much favour.

Barring Gear.—There would be some distortion of the shaft if the barring gear was not used during a shut-down and this would cause a delay in restarting, but it is thought that no permanent damage would result.

It is agreed that the motors should be connected to the emergency supplies system, if this can be done at a reasonable cost. With the installation of standby Diesel plant on larger stations, the cost involved is less than would be the case if a supply had to be taken from the batteries.

The following comments are given in reply to individual questions.

Professor Kapp.—The capital cost of installing three station transformers instead of two, would, in most cases, exceed any savings which might arise from a reduction in rating or in losses. Particularly is this the case where the transformers are connected at 275 kV.

I agree that more detailed records covering failures of plant would be of value.

Mr. Bottrell.—Nuclear stations and oil-fired stations have, until the present time, adopted the unit principle for their auxiliary systems. In nuclear stations, the reactor and the boilers and turbines associated with it can be regarded as the unit.

The problems on oil-fired stations are much reduced by the fact that all the coal plant is eliminated, including the mill group. Hence the auxiliary loading is considerably less than on a coal-fired station.

On the other hand, the percentage auxiliary load on a gas-cooled nuclear station is approximately twice that of a coal-fired station. In addition to the factors mentioned by Mr. Bottrell, there is the further problem of dealing with the delayed heat in the reactor on emergency shut-down.

With regard to circulating currents, an angle in excess of 12° is exceptional, and provided this figure is not exceeded, the system is usually satisfactory.

Automatic change-over of extraction pumps could probably be justified in some stations, depending on the plant layout and the method of operation.

It is agreed that two standby Diesel-generator sets should be provided in order to cover maintenance.

Mr. Waggott.—I agree that one of the factors governing the rating of motors in relation to voltage is the robustness of the windings, and this should certainly be taken into consideration when determining the horse-powers to be specified.

If Diesel-generators are installed, a.c. generation would appear to be preferable to d.c., because of its greater reliability and cheapness.

Mr. Hutchinson.—There have been a number of breakdowns of power-station motors in recent years, and the fault level in relation to cable size, motor rating and the design of the terminal box, has been a significant factor. The time grading for fault conditions is under review at the present time, and the suggestion made by Mr. Hutchinson is most interesting.

Mr. Abbott.—The extra civil engineering costs required for oil-break switchgear, quoted by Mr. Abbott, appear to enhance the case for air-break switchgear.

Mr. Myers.—The analysis of loads on power stations already in service will be of assistance to designers. The figures appear to confirm the design estimates given in the paper, except for the coal- and ash-handling plant. As mentioned in the paper, these plants differ considerably, and estimates in terms of kilowatts per ton can sometimes be misleading.

It is preferable to use air-break switchgear rather than contactors for the urgent auxiliaries, but this can be influenced by the relative costs. Air-blast switchgear suffers from the disad-

vantage of requiring a compressor and associated apparatus, which could be a source of trouble.

The voltage drop to 80% of normal refers to the value which might obtain when starting a boiler-feed pump in certain circumstances, and the electrical system is usually designed to ensure that the voltage does not fall below this figure. The starting characteristics of a typical boiler feed pump shown in Fig. 4 illustrates the significance of this. This problem is different from that of under-voltage protection. With regard to running conditions, motors for urgent auxiliaries are normally specified by the C.E.G.B. to remain in step for 10 min with a voltage reduction to 75% of normal.

Mr. Clarke.—Duplicate busbar switchgear for auxiliaries is not now generally used in power stations. The extra cost does not appear to be justified, as it is probable that in most instances a fault on one busbar would result in the loss of the whole board.

The construction supply from the Area Board can be incorporated into the power-station electrical system to act as a standby supply. On many sites, however, this supply is provided as a temporary installation and the cost involved in making it permanent is probably not justified, bearing in mind that it might never be used.

The cost comparison in Section 15.3 is based on oil-break gear.

Mr. Stubbs.—I agree that at 11 kV the motor ratings should not be below 1 000 h.p.

Transformers having two secondary windings have been used on some stations, but there is often difficulty in obtaining reliable figures, during the design stage, of the reactance between the two secondaries, and as this affects the switchgear rating, the whole project might be held up on this account. A further point against the use of two windings is that a fault on one winding would probably result in the loss of the complete transformer.

Mr. Miller.—Protective gear and the associated problem of earthing is, of course, an important aspect of system design, but could not be included in the paper without making it unduly long. Resistance earthing is recommended where the fault current may become excessive.

The urgent auxiliaries are protected by thermal over-current and earth-fault relays. Time-delayed under-voltage protection is provided for the mill group to prevent hazardous conditions arising in the boiler in certain circumstances. It is suggested that a 5 sec setting might be suitable in most cases, depending on the boiler characteristics and the electrical system design.

The subject of controls is outside the scope of the paper, but it can be said that there has been an advance in recent years towards complete central control.

Mr. Bradbury-Williams.—The supplies for construction purposes are usually provided, in this country, from the local Area Board. At overseas stations where there is no such supply available, Diesel-generating plant would presumably be used.

If contactors are used for urgent auxiliaries they are usually latched-in.

No difficulty has been experienced in obtaining variable-speed motors in the voltage and speed ranges for which they have been required. A.C. stator-fed commutator motors have been used extensively where variable speed is required, and are available for the different voltages used on power stations.

Fig. 5 in the paper illustrates a system which might be used for a two-line machine. A unit transformer for each line is recommended.

Mr. Garrard.—It is interesting to note that Mr. Garrard considers there would not be much difficulty in designing a 6 000 amp switchgear unit. Even this would not be adequate for the larger sets at present being installed. For instance, the 200 MW unit has a current of approximately 8 000 amp.

Mr. Molyneaux.—The question of standby plant on power stations has been the subject of much discussion in recent years, and there are many factors which need to be taken into account, which are outside the scope of this paper.

Mr. Priest.—The last two major disasters involving oil-break switchgear were at Kilmarnock in 1952 and Dalmarnock in 1954, but the switchgear installed was not of modern design. It is agreed that modern properly rated oil-break equipment has given very little trouble, but it is difficult to avoid the fact that the presence of oil constitutes a fire hazard.

Mr. Ayers.—It is difficult to comment on the proposals made by Mr. Ayers without seeing the details, but I should be surprised if separate electrical systems showed any economic gain.

The voltages used on power-station auxiliary systems correspond to those recommended by the B.S.I., and to adopt the suggestion of changing to those used on the Continent and in North America would require a great deal of discussion between many branches of the electrical industry.

Mr. Cahm.—The location of the equipment in the power station is an important consideration, and the most common arrangement is to have two main distributing centres, one at the front of the turbine house and one at the back of the boilers.

Mr. Tozer.—It is considered preferable to load the generator lightly before disconnecting the station supply, because this helps to stabilize the unit.

I agree that the electrostatic precipitator should be given a very reliable supply, and it is therefore treated as an urgent auxiliary.

The lighting- and heating-load estimate is based on design estimates and statistics of plant already in service, but, of course, this can vary depending upon the type of heating employed.

DISCUSSION ON

'THE STARTING OF A 3-PHASE INDUCTION MOTOR CONNECTED TO A SINGLE-PHASE SUPPLY SYSTEM'*

Mr. E. W. Krebs (*communicated*): I have been using the authors' method for many years and have found it a most useful and practical tool for resolving any problem involving unbalanced feeding of a polyphase motor, such as the starting performance of a single-phase motor. The only difference I could perhaps claim is a slightly different arrangement of the terms for the ratios of the various quantities. It is often an advantage if the denominator is arranged in a symmetrical manner, as it then indicates at a glance the value of a parameter for which the ratio reaches a maximum (or minimum).

For example, eqn. (15) can be brought into a symmetrical form by dividing the numerator and denominator by $6y$, resulting in

$$\frac{T}{T_b} = \frac{1}{\sqrt{3}} \frac{\sin \alpha}{1 \cdot 5/y + y/1 \cdot 5 + 2 \cos \alpha}$$

which reaches a maximum when $1 \cdot 5/y = 1$ for any fixed value of α. Similarly, eqn. (17), in its symmetrical form,

$$U = \left[\frac{\sqrt{3}/y + y/\sqrt{3} + 2 \cos (\alpha + 30°)}{\sqrt{3}/y + y/\sqrt{3} + 2 \cos (\alpha - 30°)}\right]^{1/2}$$

immediately gives a minimum for $y = \sqrt{3}$ and any fixed value of α.

The maximum starting torque occurs when the admittance of the phase convertor is equal to the admittance of the combination of the phase windings across the terminals of the phase convertor if the mains are replaced by a short-circuit. This holds not only for 3-phase star- or delta-connected windings, but also for balanced or unbalanced 2-phase windings. In the latter case, of course, a third parameter is introduced, namely the turns ratio of the main phase and the capacitor phase. Since this parameter influences the starting torque in direct proportion, it can readily be used for increasing the starting torque of a single-phase machine.

In Section 2.2.5 it is stated that 'the designer must take into account . . . the voltage across the phase convertor'. This is certainly necessary, but it must be pointed out that the voltage calculated by eqn. (22) occurs at standstill. Under running-up or running conditions the voltage across the phase convertor is normally appreciably higher, and it is obviously this higher voltage for which the phase convertor should be designed.

Dr. J. E. Brown and **Mr. C. S. Jha** (*in reply*): We are glad that Mr. Krebs has found the analysis to be 'a most useful and practical tool'. This enables us to emphasize that the whole object of the paper is to place such a tool at the disposal of the designer of single-phase machines; not to produce an academic exercise in symmetrical component theory. A similar analysis of the 2-phase case has been published in the *Proceedings*.†

Rewriting certain equations in the form suggested does lead to some simplification when considering variations of the relevant quantities with the parameter y, but there appears to be no simplification when considering the variation with α.

The most general form for the ratio of the voltage across the capacitor to the supply voltage is

$$\left|\frac{V_Y}{V}\right| = \left[\frac{y_1^2 + y_2^2 + 2y_1y_2 \cos (120° + \alpha_2 - \alpha_1)}{9 + y_1^2 + y_2^2 + 6y_1 \cos \alpha_1 + 6y_2 \cos \alpha_2 + 2y_1y_2 \cos (\alpha_2 - \alpha_1)}\right]^{1/2}$$

where, using the notation of the paper, $y_1 = |Y_1/Y|$, $y_2 = |Y_2/Y|$, $\alpha_1 = (\beta - \phi_1)$, $\alpha_2 = (\beta - \phi_2)$ and ϕ_1, ϕ_2 are the arguments of Y_1 and Y_2 respectively. (If $y_1 = y_2 = y$ and $\alpha_1 = \alpha_2 = \alpha$, the conditions which hold at standstill, this equation reduces to eqn. (22) of the paper.) For most induction motors the value of Y_2 at any speed differs very little from the standstill value Y_s. It is therefore justifiable to assume that $y_2 = y$ and $\alpha_2 = \alpha$. Then, introducing the notation $y_1 = ny_2$ and $\lambda = (\alpha_2 - \alpha_1) = (\phi_1 - \phi_2)$ gives

$$\left|\frac{V_Y}{V}\right| = \left\{\frac{y^2[1 + n^2 + 2n \cos (120° + \lambda)]}{9 + y^2(1 + n^2 + 2n \cos \lambda) + 6y[n \cos (\alpha - \lambda) + \cos a]}\right\}^{1/2}$$

If the values of y and a recommended in the paper are employed, i.e. $y = \sqrt{3}$ and $\alpha = 150°$, this expression reduces to

$$\left|\frac{V_Y}{V}\right| = \left[\frac{1 + n^2 - n \cos \lambda - \sqrt{(3)}n \sin \lambda}{1 + n^2 - n \cos \lambda + \sqrt{(3)}n \sin \lambda}\right]^{1/2}$$

This ratio is unity when λ is zero, which occurs at standstill and at a speed close to the running-light speed. Between these values $90° > \lambda > 0$ and the ratio is less than unity (it should be remembered that ϕ_2 is numerically greater than ϕ_1 and both are negative, hence λ is positive). For other values of y and α the relationships are more complex, and Mr. Krebs's warning should be borne in mind. It is hoped to deal with this point and also with the physical significance of the relationships between convertor and machine admittances in a later paper on the general properties of static phase convertors and symmetrizers.

* Brown, J. E., and Jha, C. S.: Paper No. 2860 U, April, 1959 (see 106 A, p. 183).

† Jha, C. S., and Daniels, A. R.: 'The Starting of Single-Phase Induction Motors having Asymmetrical Stator Windings in Quadrature', *Proceedings I.E.E.*, Paper No. 3049 U, August, 1959 (106 A, p. 326).

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DEVELOPMENT AND DESIGN OF SPHERICAL INDUCTION MOTORS

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SUMMARY

The first major development described is concerned with the arrangement of stator blocks. A previous paper described a system in which four stator blocks were arranged around the rotor. The new layout involves the use of only two blocks containing pre-skewed slots. The arrangement of the laminations and slotting is such that the two blocks can be rotated as a unit to produce speed adjustment. This arrangement is shown to produce a more uniform effective field velocity over the active surface of the stator. It equalizes the magnetic pull between rotor and stator and has several other design advantages which are fully discussed. The earlier theory of the spherical motor is extended to the case of machines with pre-skewed slots. Test results obtained from several experimental machines are shown. In the light of these results a procedure for designing spherical motors is developed. Several aspects concerning manufacturing procedure, such as the required numbers of rotor bars and rings, have been investigated, and the practical results of these tests are included. A short section of the paper is devoted to the performance of spherical machines when used as induction generators.

(1) INTRODUCTION

In earlier publications[1, 2] the authors have described variable-speed induction motors based on a principle illustrated in Fig. 1. A stator block, A, is wound with a polyphase winding

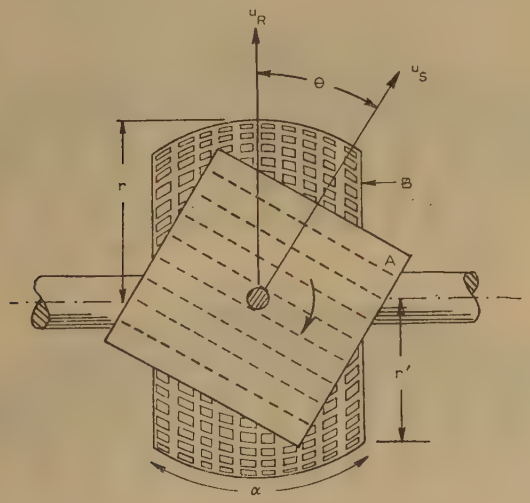


Fig. 1.—Arrangement of rotor and stator in a spherical machine.

designed to produce a field travelling across the block with velocity u_s. The inside surface of the block is part of a sphere and is concentric with the spherical surface of the rotor B, which can carry current in any surface direction. The rotor will approach the synchronous speed

$$u_r = u_s/\cos\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The stator block can be rotated so as to vary θ while maintaining a uniform air-gap between rotor and stator, and hence u_r can be controlled. Speed ranges as high as 6 : 1 have been achieved, and there is no theoretical reason why any desired speed range should not be possible.

The stator is essentially made up of several individual blocks. Unenergized rotor material is continuously entering the area of influence of each stator block, becoming energized, and then leaving the block in an energized condition. The system is never free from the influence of transients, and the flux density over the surface area of any block is non-uniform.

A theory accounting for these transient effects has been developed[2] for the case of $\theta = 0$. The theory assumes a travelling wave of current density $j_s = J_s \sin(\omega t - \pi x/p)$ in the stator block shown in plan in Fig. 2.

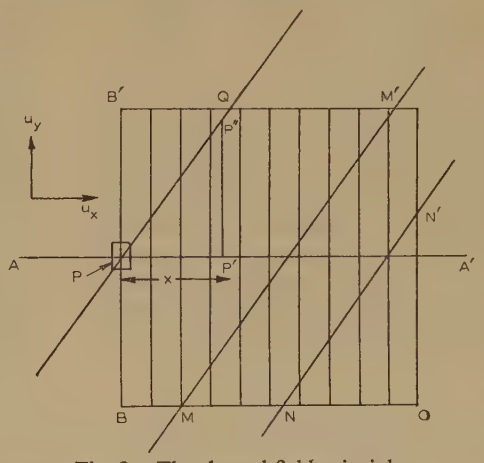


Fig. 2.—The skewed field principle.

The lines drawn in the Figure do not represent slots, but are lines of constant phase of the current distribution. The theory considers the factors influencing an element of rotor, P, as it passes under the block, along the axis of x, AA'. The line BB' is taken as the origin of x, so that the position of P after time t is $x = u_x t$, shown at P', where u_x is the velocity of P in the direction AA'.

The theory, which includes some approximations, enables the flux density at all points under the stator to be calculated for the particular case of $\theta = 0$ [eqns. (13) and (14) of Reference 2].

If now the rotor is given an additional velocity u_y in the direction BB', the element will in fact arrive at P'', where x has the same value as before and $y = u_y t$. It may be seen, however, that the element is still embraced by the same pair of equiphase lines, and its behaviour is therefore unchanged by the introduction of u_y. The theory developed for the case of $\theta = 0$ can be applied to cases where $\theta \neq 0$, provided that x and p and all quantities derived therefrom are measured in the direction of motion of the current wave, and j_s is the current density in that direction.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
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The velocity u_y, however, will not be altogether without effect. Thus the element P will emerge from the block at point Q instead of A′, thereby reducing the effective length of the block and therefore the range of x over which the flux equations apply.

Furthermore, not all elements will now enter the block along BB′; some may enter at points such as M and leave at M′, or at points such as N and leave at N′. In both cases there is a reduction of effective block length, and for the theory to apply it will be necessary to treat x as zero at the entry point, whatever it is, and not as zero on the extension of B′B. Detailed analysis of these effects is not necessary here; it will suffice to note that the efficiency of the machine was shown to depend very much on the number of poles (n) of the travelling wave contained within the block length in the direction of motion of the rotor, good efficiencies being possible only for values of n in excess of about 4. The greater u_y is made relative to u_x, i.e. the greater θ becomes, the greater will be the effective reduction of block length, and therefore of pole number. Thus, the greater the speed range of the machine, the smaller will be the effective number of poles relative to the actual number on the block in the x-direction. Hence, if the effective number of poles at the highest speed is to be sufficient, say greater than 4, then the greater the speed range required, the greater will be the actual number of poles on the block and therefore the smaller will be the pole pitch for a given block length. Small pitches result in inefficient machines.

(2) THE 4-BLOCK TYPE OF CONSTRUCTION

In the machine described in a previous paper,[2] four sets of movable stator blocks were envisaged, each of which was a 'square' of side r, equal to the rotor radius. In the earlier machines the rotor arc α under a block was restricted to 60°. Having restricted the block width, the block length is now similarly restricted. If, for example, a 2 : 1 speed range is required, the stator blocks must be rotated through 60°. If the block dimension in the direction of the field velocity is greater than that in the direction of the slots, a large portion of the stator surface will have been turned clear of the rotor surface at top speed. The number of poles in the direction of motion of the rotor is now halved. The best efficiency at 50 c/s on a 4-block machine with a 14 in-diameter rotor was 33% at bottom speed, with much lower efficiencies at higher speeds.

The error made in designing this machine was to start from the minimum-speed condition and then see how far the performance deteriorated at higher speeds. By starting from $\theta = 0$ large angles of rotation are necessary before any useful speed range is obtained [see eqn. (1)].

(3) THE 2-BLOCK TYPE OF CONSTRUCTION

A new type of construction was designed to enable the block length in the direction of motion to be extended. Segmental stator punchings can be offset with respect to each other so as to produce pre-skewed slots as shown in Fig. 3, where the punching thickness has been exaggerated to illustrate the method. If all the punchings are identical, the edges of the block are serrated as shown. The individual punchings are arranged to lie in radial planes so that no machining of the inner surface is necessary. Furthermore, these planes are arranged to pass through the rotor axis when the block is in its central position, so that in terms of rotor movement the laminations could be said to lie at right angles to the direction of those in a conventional machine. The method of construction is illustrated in Fig. 4. Segmental punchings are stacked against a pair of accurately spaced rings. The serrated edges are not

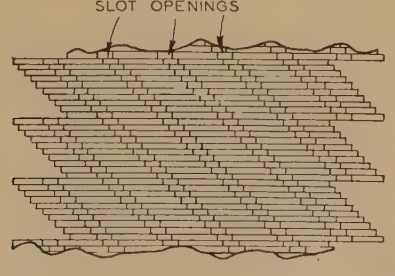


Fig. 3.—Assembly of laminations forming pre-skewed slots.

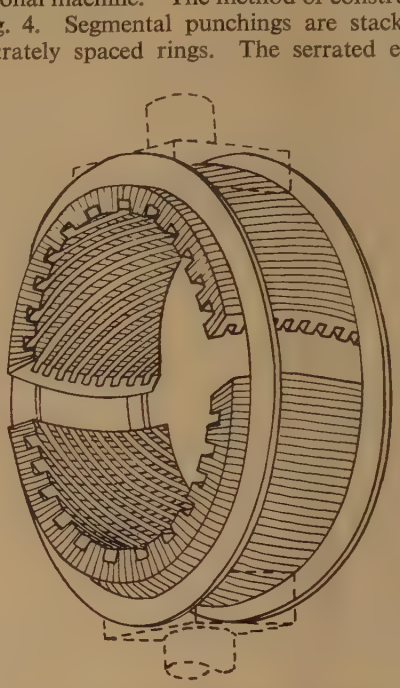


Fig. 4.—Two-block type of construction.



Fig. 5.—Types of stamping used in stator construction.

shown in this diagram for the sake of clarity. Each stamping is kept in a radial plane by suitable incorporation of truncated stampings in the right proportion (as shown in Fig. 5). To assist in stacking, a dummy rotor was made, being oversize by the amount of the air-gap. This can be seen in Fig. 6, which shows a machine in process of construction.

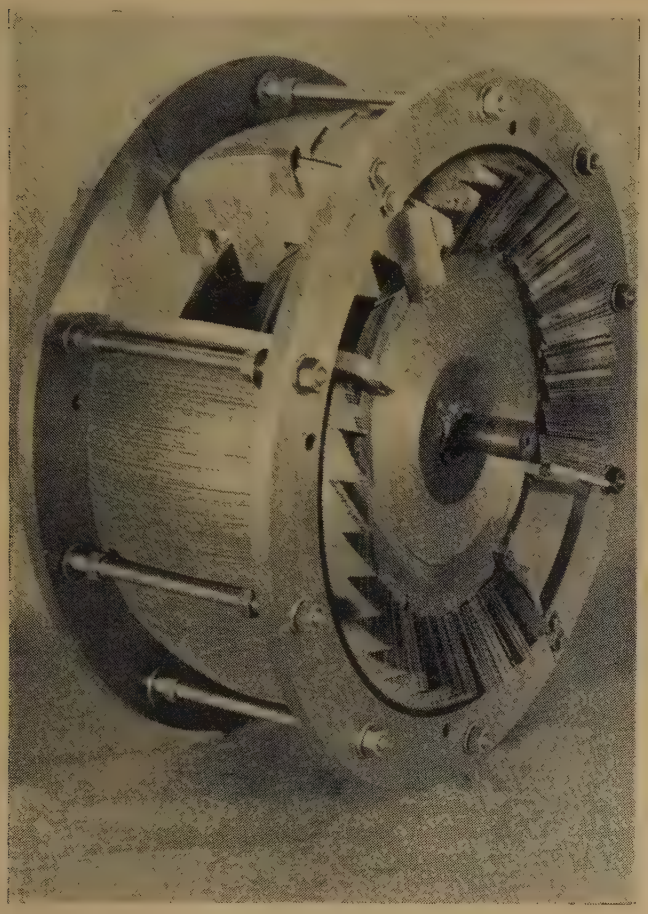


Fig. 6.—Method of stator construction.

Laminations were stacked to fill the first 5° with radially-disposed laminations, as shown.* This packet was given a skew of one slot pitch. The punchings were held together by clamps; the inner surface was pressed into contact with the dummy rotor, and a light weld was run along the back surface to hold the packet together. When sufficient packets had been made, they were stacked between end plates on the dummy rotor, with the slots aligned but advanced relative to each other by one slot per packet.

Two strips of thin steel were welded to the backs of the packets to form one stator block. These were used to anchor the block to the bolts joining the forming rings.

It is apparent from the geometry that each point on the rotor surface crosses the same number of slots as it traverses the block. In other words, there is no velocity discrepancy so long as the stator block is in the central position. Rotation of both blocks together as a unit produces an effective increase in θ in each block, or a reduction in θ in each.

The first 2-block machine built had a 45° pre-skew. With this arrangement $\pm 18\frac{1}{2}°$ rotation of the stators is sufficient to give a speed range of $\cos 26\frac{1}{2}°/\cos 63\frac{1}{2}° = 2:1$. With such comparatively small stator displacements, very little of the stator surface is turned off the rotor edge even though each block subtends nearly 180°.

There are several advantages in such a form of construction, namely

(*a*) The increase in block length compared with a 4-block machine of the same speed range enables either an increase in pole numbers or an increase in minimum pole-pitch to be obtained on a given size of rotor. Both these features are known to give improved performance.

(*b*) At one speed setting, i.e. with the axis of the stator forming-rings coincident with the axis of the rotor, there is no velocity discrepancy.

(*c*) Since both blocks can be rotated as a unit, there is ideally no magnetic thrust on the stator bearings as there is in the 4-block type.

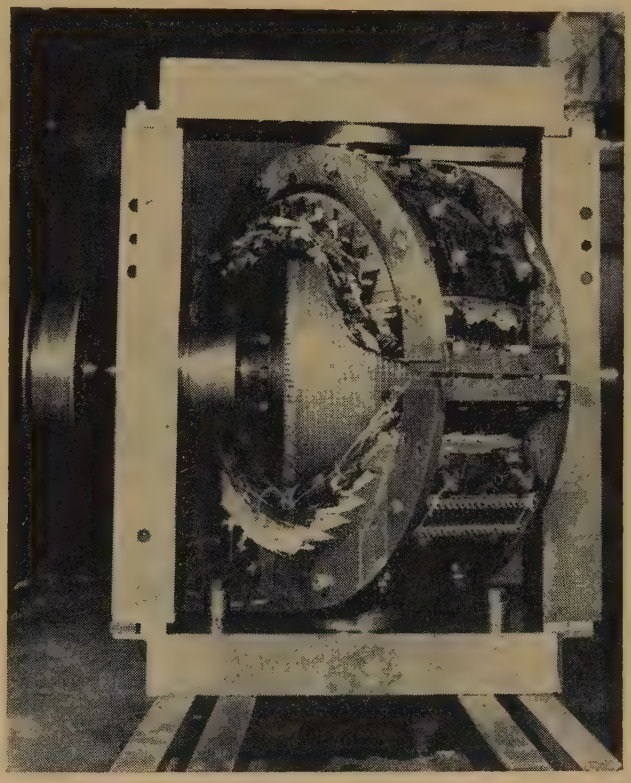


Fig. 7.—A complete 2-block machine ($63\frac{1}{2}°$ pre-skew).

The remaining mechanical details are summarized in Fig. 7 which shows one of the later complete machines with a $63\frac{1}{2}°$ pre-skew.

(3.1) Application of the Theory to Pre-Skewed Machines at Mid-Position

It has been pointed out that, when the stator blocks are centrally placed over the rotor, every element of the rotor spends the same time under the block and crosses the same number of slots. No rotor elements either enter or leave the sides of the block. Thus, for all rotor elements the effective number of poles on the block is the number of poles measured in the direction of motion of the rotor.

The theory developed in Reference 2 is thus fairly easily applied to the block in the central position where $\theta = \theta_0$, and θ_0 is the angle of pre-skew. In particular, the equations for the component of flux density B_p, which is in phase with the stator

* This is the figure appropriate to about 45° skew with 12 slots per segment. The machine actually shown in Fig. 6 is a later model with $63\frac{1}{2}°$ skew which involves the use of 10° packets.

current J_s, and the component B_q, which is in quadrature with J_s, can be rewritten as

$$B_p = \frac{\rho_r J_s \pi}{p\omega} \frac{\sigma}{\sigma^2 + (1/\tau\omega)^2} \left\{1 - \exp\left[\frac{-\psi}{\tau\omega(1-\sigma)}\right]\right\}\left[\cos\frac{\sigma}{1-\sigma}\psi + \frac{1}{\sigma\tau\omega}\sin\frac{\sigma}{1-\sigma}\psi\right] \quad . \quad . \quad . \quad . \quad (2)$$

$$B_q = \frac{\rho_r J_s \pi}{p\omega} \frac{1/\tau\omega}{\sigma^2 + (1/\tau\omega)^2} \left\{1 - \exp\left[\frac{-\psi}{\tau\omega(1-\sigma)}\right]\right\}\left[\cos\frac{\sigma}{1-\sigma}\psi - \tau\omega\sigma\sin\frac{\sigma}{1-\sigma}\psi\right] \quad . \quad . \quad . \quad . \quad (3)$$

These equations have been obtained from eqns. (13) and (14) in Reference 2 by writing

$$\tau = 4p^2\mu_0/\pi\rho_r g \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$p\omega/\pi = u_s \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and

$$\psi = \pi s/p \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Of these quantities, τ is rotor time-constant, and ψ is the distance in electrical radians which a rotor element, now situated at the point where the flux density is measured, has travelled under the stator block since entry. For example, in Fig. 2 for the flux density at P″ the relevant value of ψ is PP′ expressed in electrical radians of the current wave. $p\omega/\pi$ has been written for u_s to eliminate any confusion between wave velocity in the direction of the wave motion (u_s) and actual rotor synchronous speed, $u_s/\cos\theta$. It is important to remember that the symbols J_s, p, u_s and s relate to a direction perpendicular to the slots and not to the direction of rotor movement.

In Reference 2 the torque/slip curve and the rotor-copper-loss/slip curve were developed for the ideal case of a machine with no air-gap. A brief outline of the extra losses occurring at the exit edges of the stator blocks was attempted. These calculations are now extended, using eqns. (2) and (3) to include finite values of decrement, and a set of curves showing exit-edge loss variation with slip is added. Prediction of the performance of pre-skewed machines may now be attempted for the $\theta = \theta_0$ condition.

(3.2) Rotor Copper Loss

Rotor copper loss $= \frac{1}{2}\rho_r \int_0^{np} J_r^2 ds$, where J_r is the rotor current density, and may be written

$$J_r^2 = (J_s - J_{mp})^2 + J_{mq}^2$$

J_{mp} represents the component of J_s which sets up B_q, and J_{mq} the component of J_s setting up B_p.

As in Section 12.1 of Reference 2 it is assumed that J_{mp} and J_{mq} may be written

$$J_{mp} = gB_q/4p\mu_0 \text{ and } J_{mq} = gB_p/4p\mu_0$$

whence

$$\tfrac{1}{2}\rho_r\int_0^{np} J_r^2 ds = \tfrac{1}{2}\rho_r\int_0^{np}\left[J_s^2 - \frac{2J_s g}{4p\mu_0}B_q + \left(\frac{g}{4p\mu_0}\right)^2(B_p^2 + B_q^2)\right]ds \quad . \quad . \quad . \quad . \quad (7)$$

Evaluation of the rotor copper loss from this expression is completed in Section 10.1.1.

(3.3) Torque/Slip Curves

The total force, F, exerted tangentially by a stator block is given by

$$F = \frac{J_s}{2}\int_0^{np} B_p ds$$

Substituting for B_p from eqn. (2) gives

$$F = \frac{\rho_r J_s^2}{2u_s}\frac{\sigma}{\sigma^2 + (1/\tau\omega)^2}\int_0^{np}\left\{1 - \exp\left[-\frac{\psi}{\tau\omega(1-\sigma)}\right]\right.$$
$$\left.\left[\cos\frac{\sigma}{1-\sigma}\psi + \frac{1}{\tau\sigma\omega}\sin\frac{\sigma}{1-\sigma}\psi\right]\right\}d\psi \quad . \quad (8)$$

The integration is completed in Section 10.1 and expressed as Fu_s.

(3.4) Magnetic Energy

Rotor elements enter the stator arc in an unenergized condition. As they pass under the block, magnetic flux is built up in the elements in accordance with eqns. (2) and (3). On reaching the end of the block the total flux density in the element is

$$B_x = \sqrt{(B_{px}^2 + B_{qx}^2)}$$

Associated with this flux density there is stored energy

$$\frac{1}{2}\left(\frac{B_x^2}{8\pi\mu_0}\right) \text{ per unit volume of gap}$$

This magnetic energy has been acquired during transit, and the rate of arrival of magnetic energy, non-existent at the entry edge, is

$$\frac{1}{2}\frac{(B_{px}^2 + B_{qx}^2)}{8\pi\mu_0} g u_r \text{ per strip of stator of unit width.}$$

It is necessary for this magnetic energy to be very largely dissipated before re-entry under the block. The phase of the 'carried over' flux as it re-enters will in general not be ideally disposed for the production of useful drive torque. It has been verified in practice that the carrying-over of flux results in undesirable undulations of the speed/torque curve, especially in the working range, since any flux carried over may either aid or oppose the wanted flux, depending on the speed setting (θ) and the slip, and tends always to favour synchronous speeds corresponding with even pole numbers, as would be expected by analogy with conventional machines.

It was suggested in the previous paper that the desired dissipation of exit-edge flux could be achieved by arranging for the rotor time-constant outside the block to have a value $\tau_0 = \tau/\lambda$, where $\lambda > 1$ and is chosen to dissipate the flux over the arc-length available between blocks. It was suggested that if this were done the magnetic energy being transported away immediately outside the block would be λ times that being transported under the block, i.e. the stator exit-edge loss P_x would be given by

$$P_x = \tfrac{1}{2}\lambda g\frac{(B_{px}^2 + B_{qx}^2)}{8\pi\mu_0}u_r \quad . \quad . \quad . \quad . \quad . \quad (9)$$

where λg is the gap which would be required outside to give the time-constant τ_0, assuming no rotor leakage.

Eqn. (9) can be re-expressed as

$$P_x = \frac{1}{2}\frac{\tau}{\tau_0} g\frac{(B_{px}^2 + B_{qx}^2)}{8\pi\mu_0}u_r$$

It is convenient in the design procedure considered later to

express $\tau\omega$, whenever it appears, in terms of the time t_s spent under the block by a point travelling at speed u_s, whence $t_s = np/u_s$.

Thus
$$\frac{P_x}{t_s/\tau_0} = \frac{1}{2}\frac{g}{8\pi\mu_0}(B_{px}^2 + B_{qx}^2)\frac{u_r}{t_s/\tau} \quad . \quad . \quad . \quad (10)$$

In a practical machine τ_0 must be chosen in appropriate relation to the time elapsing between leaving one block and entering the next, since it defines the time required to dissipate all but $(1/\varepsilon)^2$ of the transported energy. The quantity $P_x(\tau_0/t_s)$ is evaluated in Section 10.1. The general form of this exit-edge loss is shown by Fig. 8, which represents eqn. (26) plotted for $n = 4$ and various values of t_s/τ.

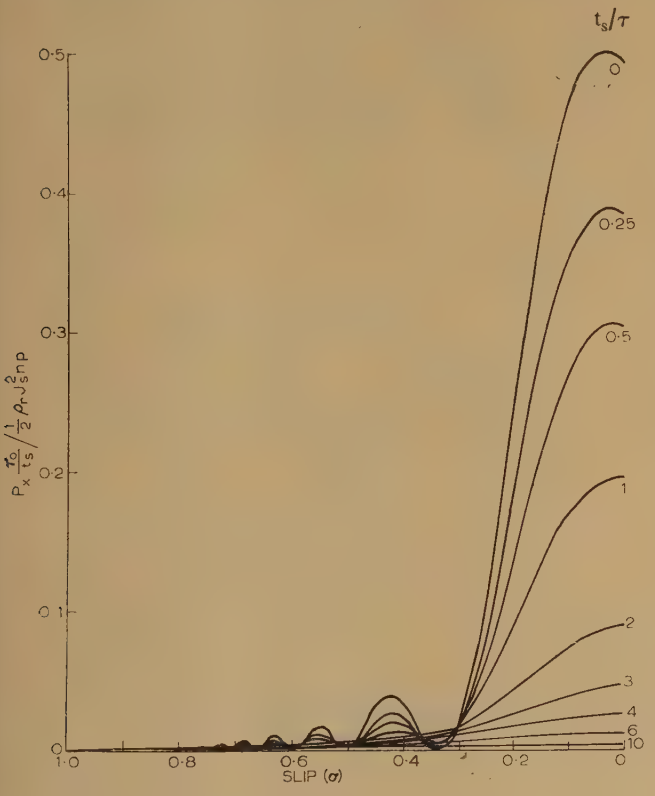


Fig. 8.—Theoretical curves of exit-edge loss.

(4) EXPERIMENTAL RESULTS

(4.1) The First Machine with Pre-Skewed Slots

Stator rotation was limited mechanically to $\pm 12°$. The stator blocks had a pre-skew angle of 45°, and the arc length in the direction of motion of the rotor was made as large as possible, the limiting factor being the space required for the end turns of the winding. The arc length was in fact 140°, whilst each segmental stator punching subtended 60° and carried 12 slots. The two slot per pole per phase, 5/6 chorded, double-layer winding therefore produced two pole-pitches of m.m.f. wave across every stator lamination, and therefore 4·67 pole-pitches around the 140° arc. The synchronous speed for the central position was therefore 500 r.p.m. when using 50 c/s supply.

The first series of experiments was designed to verify that the theory developed in Reference 2 was applicable to the pre-skewed machine in the manner outlined in Section 1. A flux analysis was carried out with the stator blocks central ($\theta = \theta_0$) in accordance with the method described in Reference 2, Section 4, due allowance being made for leakage flux. The results of this experiment are shown in Figs. 9 (*a*)–(*e*). The curves represent the calculated flux densities using eqns. (2) and (3).

The agreement between the calculated and observed values of B_p and B_q was taken to be ample evidence that the original theory could be relied upon, at least for values of n greater than 4.

(4.1.1) Load Test.

The torque/speed curves of this machine were obtained using an acceleration method at low voltage.[3]

A load test was performed at constant current so that direct comparison with the predicted curves of synchronous watts and input could be made. The calculation of stator exit-edge loss involves the determination of λ. In the absence of a calculated value, λ was derived by measuring the time-constant τ_0 outside the block. To do this, two search coils were mounted on non-magnetic supports at different distances from the exit edge, and readings of flux density in these coils were taken when the machine was running light, from which τ_0 was calculable. The magnetic energy arriving at the exit edge has been supplied directly by the stator. If the stator iron continues beyond the end of the stator winding, so that the gap outside equals the gap inside, there is no back-torque on the rotor. If the gap increases outside, as is the case in practice, then power $[B_x^2 u_r(\lambda - 1)g]/8\pi\mu_0$ per unit width is supplied as mechanical work by the rotor, i.e. there is an appropriate back-torque. The remaining power $B_x^2 u_r g/8\pi\mu_0$ is supplied as before by the stator directly.

The calculated performance curves were obtained as follows. The output/slip curve was plotted from the torque equation derived in Section 10.1 and computed for $n = 4{\cdot}67$. From the ordinates of this curve were subtracted $(\lambda - 1)/\lambda$ times the exit-edge losses plotted in a similar manner to those in Fig. 8 computed again for $n = 4{\cdot}67$. This is the real output curve. To this is added the calculated rotor copper loss as derived in Section 10.1, together with $1/\lambda$ times the exit-edge loss to give a synchronous-watts curve. A final addition of calculated stator copper loss gives the intake/slip curve. The full lines of Fig. 10 represent the calculated curves, while the points are the corresponding experimental values. The agreement is remarkably good considering the approximations made, one of the most satisfactory features being the ability to predict the failure of the machine to reach the calculated synchronous speed (in this case 1 000 r.p.m.).

(4.1.2) Variations in θ.

Load tests were carried out at minimum (33°) and maximum (57°) values of θ, and at $\theta = \theta_0$ using a 50 c/s supply. The intake and synchronous-watts curves, for constant-voltage operation, and power factor/slip and efficiency curves are shown in Fig. 11. The performance at 57° was disappointing. The efficiency had fallen considerably from the values at the other settings, the peak output at constant voltage was lower than at $\theta = \theta_0$, and the power factor was lower. Investigations into the reasons for the poor top-speed performance led to a detailed mathematical analysis to determine the effective speed of the field at different points on the rotor surface. A ratio $\gamma = u_r \cos\theta/u_s$ has been calculated for all points on the rotor surface, assuming that the velocity at the centre of the stator block is equal to $u_s/\cos\theta$. The analysis is performed in Section 10.2, and the lines on Fig. 12 are lines of constant γ.* The discrepancies are more serious in the case of $\theta > \theta_0$ than of $\theta < \theta_0$, for stator components of lower speed than the demanded value will produce back-torques in the working region, whilst components of higher speed, as appear when $\theta < \theta_0$, only come fully into effect when the slip is negative.

* The projection found most useful in describing spherical motors is the 'plate carée' projection in which degrees of longitude and latitude are represented as uniform scales of x and y respectively on a Cartesian co-ordinate system. The shaded areas in Fig. 12 correspond with regions of the stator which are traversed by rotor surface.

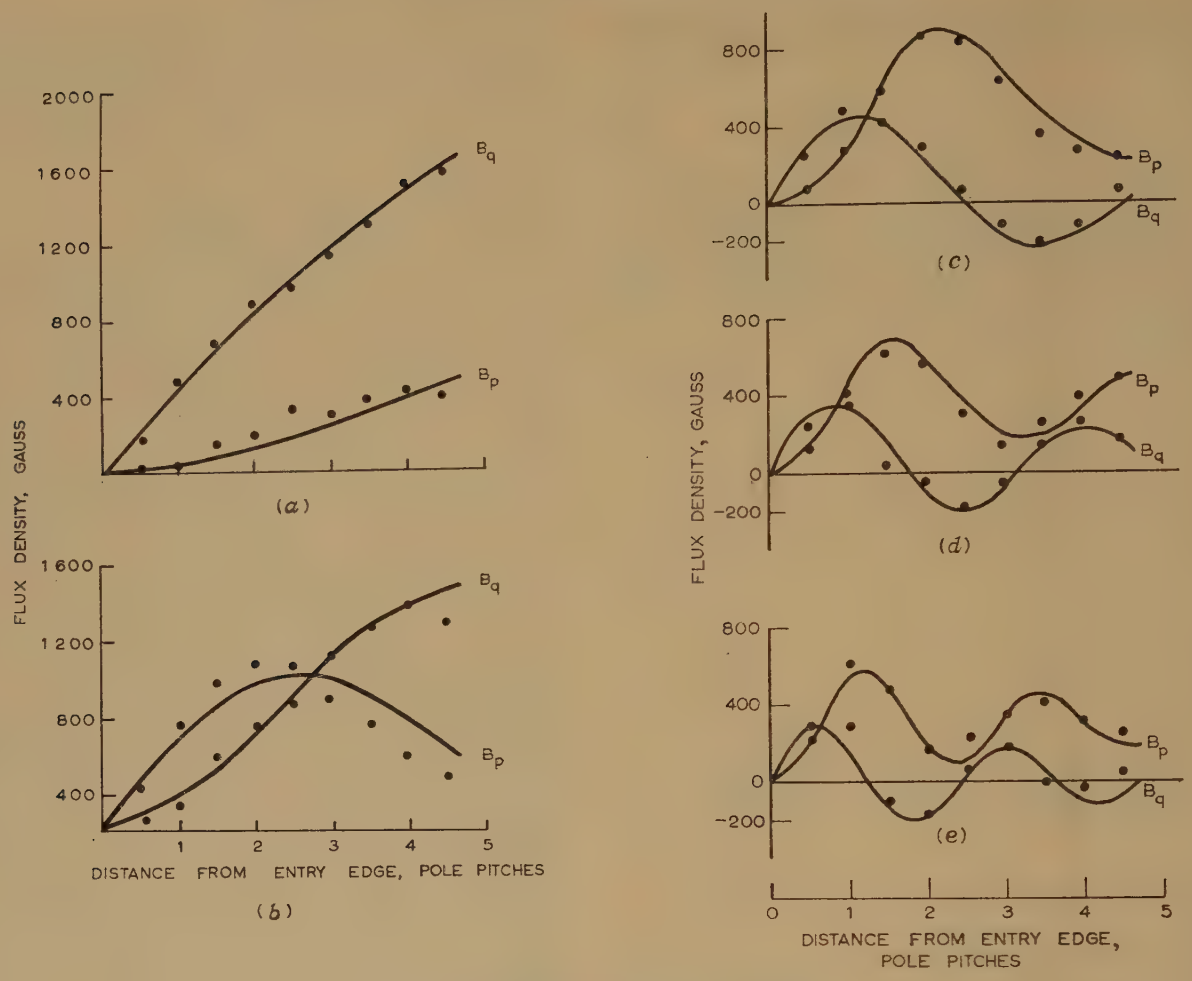


Fig. 9.—Flux distribution under a stator block.
(*a*) $\sigma = 4\%$.
(*b*) $\sigma = 1/(n+1)$.
(*c*) $\sigma = 2/(n+2)$.
(*d*) $\sigma = 3/(n+3)$.
(*e*) $\sigma = 4/(n+4)$.

(4.1.3) **Conclusions Drawn from the First Machine.**

The results of the first machine were quite pleasing in that the motor had reasonably good characteristics for the range $\theta = 33°$–$45°$ and would doubtless have been almost equally good below 33° had the mechanical arrangement permitted. The performance at $\theta > 45°$ was poor for several reasons.

(*a*) The peak output was reduced mainly because part of the stator block was turned off the rotor. This effect probably helped to lower the power factor also.
(*b*) The efficiency was lower because the number of poles was reduced.
(*c*) The efficiency and output were lower because of velocity discrepancies.

These facts could be summarized by saying that the machine was satisfactory for about 1·4 : 1 range only.

(4.2) Designing for Peak Performance at Top Speed

The next stage in the development is fairly obvious. The angle of pre-skew should be increased so that $\theta = \theta_0$ represents the top-speed condition where it is thought desirable to have maximum output, best efficiency, and so on, with the stator block centrally placed. All the stator surface is usefully employed, and there is no velocity discrepancy. The pole number can be arranged to be any desired value by design.

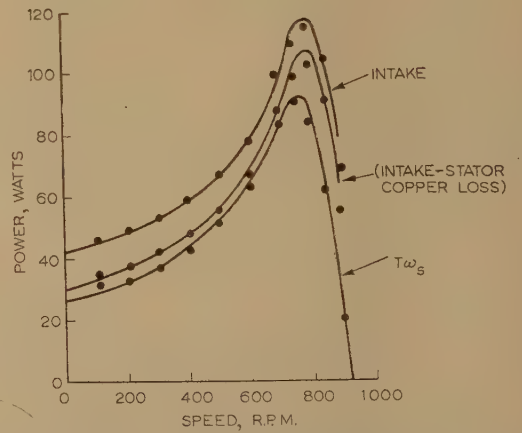


Fig. 10.—Load tests at 100 c/s on 45° pre-skewed machine.
——— Theoretical curves.
● ● ● Experimental results.

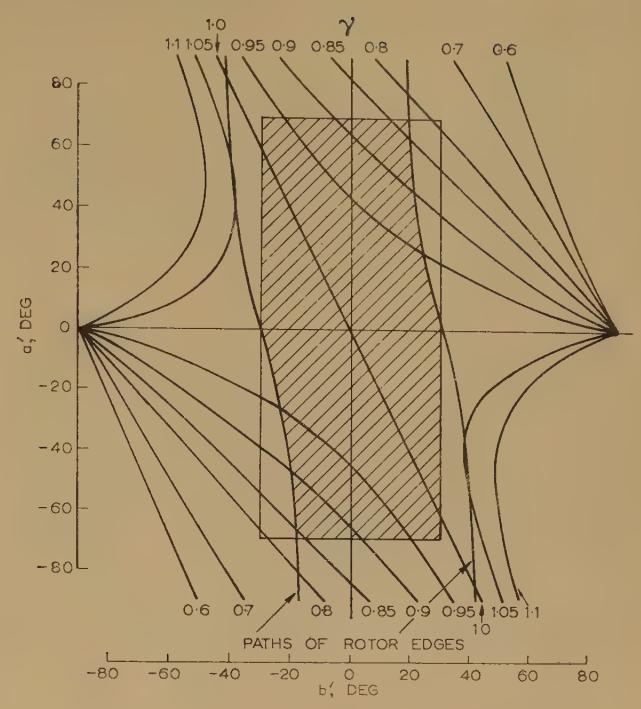


Fig. 11.—Performance curves for constant-voltage operation.

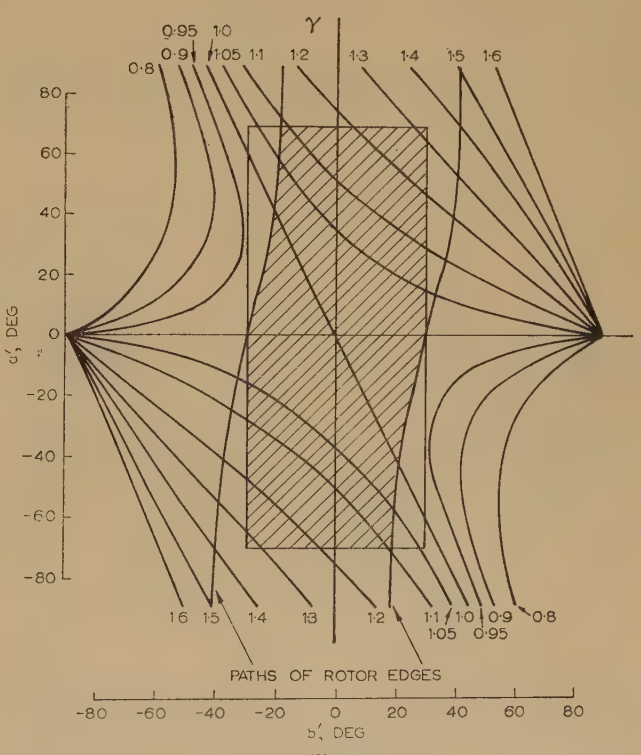
(4.2.1) **The Second Pre-Skewed Motor.**

Accordingly, a second motor was built with a view to a 2 : 1 speed range. The value of θ_0 was $63\frac{1}{2}°$ and θ could be varied down to 27° to give the desired range. The winding was designed to give 4·67 poles around 140° at top speed. This involved the use of four poles across the arc α. Using a 12-slot segment, the winding had one slot per pole per phase and was 2/3 chorded.

The main interest in this machine was the performance at top speed. A load test on 50 c/s supply at constant current yielded the results shown in Fig. 13(*a*). The cross at peak torque was obtained when the machine was delivering 5·1 h.p. The only difference in the high-power points is an increase in stator copper loss, and in rotor copper loss at standstill, both being due to the increased resistance at higher temperatures. Even though the mechanical construction was superior to that of the first machine and a smaller air-gap was obtained, the peak efficiency was reduced to 46%, with $n = 4{\cdot}67$ as before. The theoretical calculations based on eqns. (2) and (3) enabled an explanation of the poor performance of the second machine to be given. Fig. 13(*a*) shows that the low efficiency is largely due to excessive stator copper loss. The ratio between the stator and rotor copper losses at standstill is seen to be about 0·82 and, had the coupling been good, the efficiency might have approached the value calculated from the simple theory[2] which showed that for $t_s/\tau = 0$, the output was equal to n times the rotor copper loss, and that rotor and stator current densities were equal. Using this theory, and neglecting iron loss and exit-edge loss, an efficiency of $4{\cdot}67/(4{\cdot}67 + 1 + 0{\cdot}82) = 72\%$ would result. However, it is clear from Fig. 13 that the stator copper loss at



(*a*)



(*b*)

Fig. 12.—Velocity discrepancies for 45° pre-skewed machine.
(*a*) $\theta = 33°$.
(*b*) $\theta = 57°$.

full-load slip of $1/(n + 1)$ is a great deal bigger than $(0{\cdot}82 \times \text{output})/4{\cdot}67$.

Eqns. (7) and (8) may be used to predict the efficiency providing the value of t_s/τ is known. The value of τ was measured using the standstill method described in Section 4.1 and was

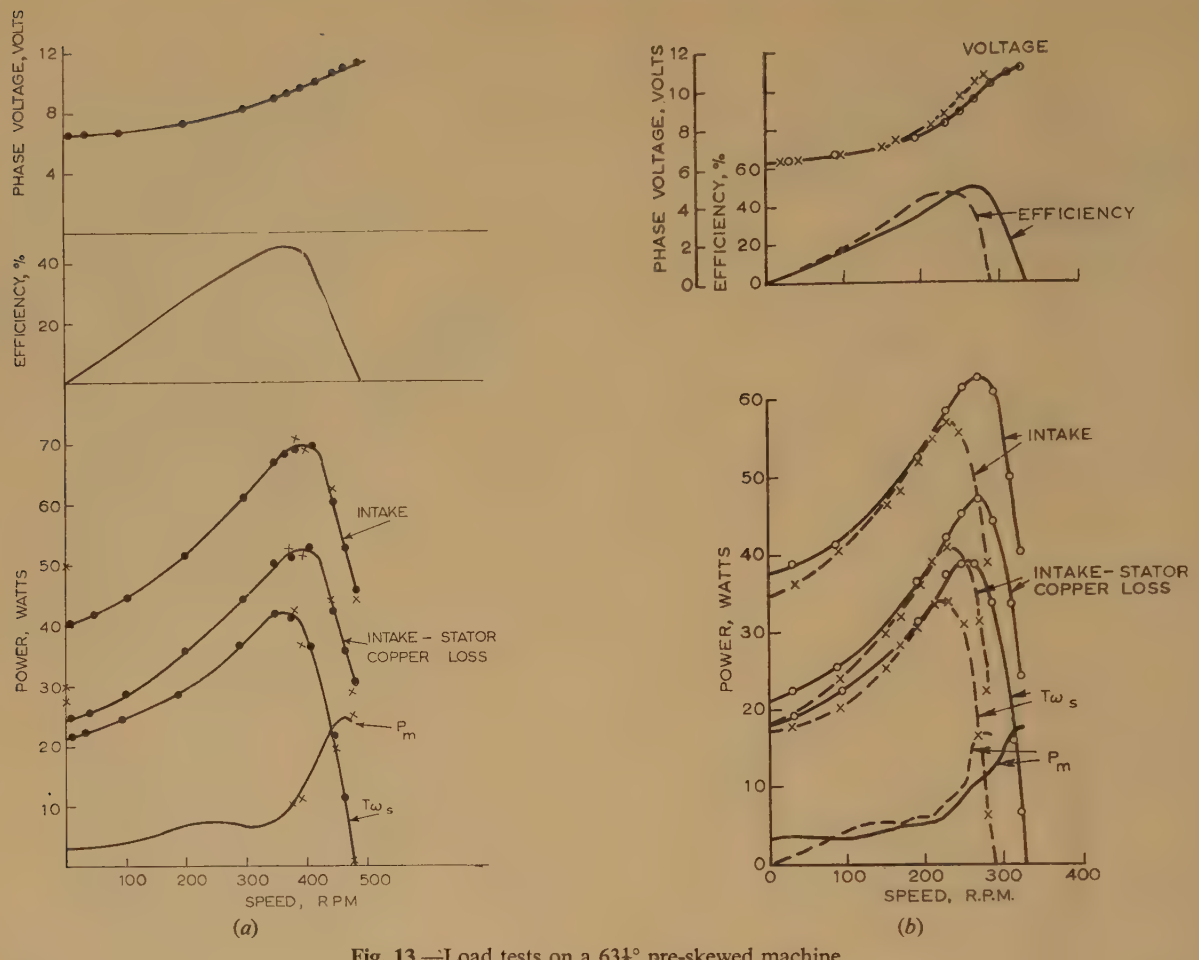


Fig. 13.—Load tests on a 63½° pre-skewed machine.

(*a*) θ = 63½°.
● ● ● Results of constant-current test.
× × × Scaled results from constant-voltage test.
(*b*) —— ○ —— ○ —— θ = 45°.
--- × --- × --- θ = 27°.

found to give a value of $t_s/\tau = 3{\cdot}1$. For this value, the peak torque occurs at approximately 25% slip.

Using eqns. (7) and (8) for $n = 4{\cdot}67$, the output per unit of stator copper loss at a slip of 25% is $1{\cdot}36\rho_r/\rho_s$ units. The corresponding rotor copper loss per unit of stator copper loss is $0{\cdot}51\,\rho_r/\rho_s$. Hence the efficiency predicted is

$$\frac{\dfrac{1{\cdot}36}{0{\cdot}82}}{\left(\dfrac{1{\cdot}36}{0{\cdot}82}+\dfrac{0{\cdot}51}{0{\cdot}82}+1\right)} = 50\%$$

The difference between this value and the measured efficiency is presumed to be due to iron loss and stator exit-edge loss. The high value of t_s/τ in this second machine compared with the first is due entirely to the increase in pre-skew which was effected whilst maintaining the same number of poles at top speed. This reduced the pole pitch by $\cos 63\frac{1}{2}°/\cos 45° = 0{\cdot}63$. Had not the air-gap been reduced at the same time, the value of t_s/τ in the first machine would have been multiplied by $(1/0{\cdot}63)^2$ to become 5·0, and the efficiency would have been even lower than 46%. Comparison of the first two machines brought out clearly the fact that, on a given frame size, severe penalties were incurred by demanding too small a pole pitch, which in this case was the result of demanding too high a speed range.

When θ was changed, the efficiency remained fairly constant, and the properties of the machine at $\theta = \theta_0$, poor as they were, were made very little worse by the reduction of θ, as is illustrated by the results of load tests at angles of 45° and 27° shown in Fig. 13(*b*). The relevant velocity discrepancy diagram for $\theta = 27°$ is shown in Fig. 14.

(4.2.2) A Machine with a Small Pole Number.

One further experiment was performed on the second machine. The 4 × 4·67 pole winding was replaced with a 2 × 2·33 pole, 2-slot per pole per phase winding. The results showed that the peak efficiency of 45% was now much nearer that predicted by the simple theory, i.e. $2{\cdot}33/(2{\cdot}33 + 1 + 0{\cdot}82) = 56{\cdot}0\%$. The value of t_s/τ for this motor is one-quarter that of the 4 × 4·67 pole machine.

(5) THE DESIGN EQUATIONS OF A PRE-SKEWED MACHINE

After the experiments on the 2-block type of machine had been completed, it was clear that certain parameters could be adjusted to give optimum performance for a given frame size and speed range. For example, it seemed likely that a machine with a 14 in-diameter rotor having a 2 : 1 speed range would have the best efficiency if n were chosen to be between 2·33 and 4·67.

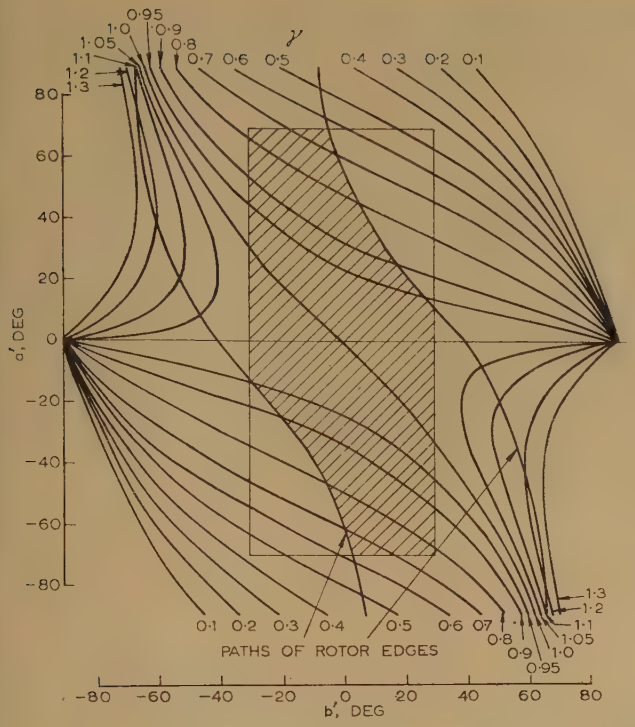


Fig. 14.—Velocity discrepancies for 63½° pre-skewed machine with $\theta = 27°$.

Having verified the theoretical arguments outlined in Sections 1 and 3 for the behaviour of pre-skewed machines, and being convinced that designing for optimum performance at top speed is advantageous, the authors set out the rules of short stator theory in the form of fundamental design equations for pre-skewed machines as follows, the full-load condition being taken to occur at a slip of $1/(n+1)$.

(5.1) Rotor Time-Constant

The arc length subtended by one stator block in the direction of motion of the rotor when $\theta = \theta_0$ may be expressed as $k_1 \times 2\pi r$, where r is the rotor radius.

The pole pitch in the direction of motion of the rotor in this position is $2\pi r k_1/n$, whence the pole pitch p in the direction of motion of the stator m.m.f. is $(2\pi r k_1/n)\cos\theta_0$. It follows that

$$\tau = \frac{4p^2\mu_0}{\pi\rho_r g} = \frac{16\pi r^2 k_1^2 \mu_0 \cos^2\theta_0}{n^2\rho_r g} \times 10^{-9} \text{ in C.G.S. units.}$$

The time t_s spent under the block at synchronous speed is $n/2f$, where f is the supply frequency. Hence

$$\frac{t_s}{\tau} = \frac{n^3\rho_r g 10^9}{32 f\mu_0 \pi r^2 k_1^2 \cos^2\theta_0} = K_3 \text{ (say)} \quad . \quad . \quad . \quad (11)$$

(5.1.1) Rotor Copper Loss.

For perfect coupling, the rotor copper loss would be $\frac{1}{2}\rho_r J_s^2 \times$ (block area). For $t_s/\tau \neq 0$, the rotor current is modified and the copper loss is calculated in accordance with eqn. (23) of Section 10.1. As this is a complicated function of n and K_3 it is convenient for the purposes of design to write the rotor copper loss as $\frac{1}{2}\rho_r J_s^2 k_\tau$ (block area), where k_τ can be read from a set of curves for different values of n and K_3 from eqn. (23) when desired. It is also convenient to calculate in terms of the current per slot, whence the chording factor k_5 must be introduced to give

$$\frac{\frac{1}{2}\rho_r J_s^2 k_\tau}{k_5^2} \text{ (block area)} = \text{rotor copper loss} = K_1$$

For a rotor of axial length equal to rotor radius (i.e. $\alpha = 60°$) the total spherical surface area $= 2\pi r^2$, whence the block area $= 4\pi r^2 k_1$ and

$$K_1 k_5^2 = 2\pi r^2 k_1 \rho_r J_s^2 k_\tau \quad . \quad . \quad . \quad . \quad . \quad (12)$$

(5.1.2) Flux Density.

Since the flux density is non-uniform it would be advantageous to utilize available space for winding where the flux density was low, i.e. at the entry edge. The method of construction proposed prohibits graded slot sizes, however. In any case a graded machine would be limited to rotation in one direction only. The punchings must, therefore, be designed to contain the peak flux density, which at full-load slip occurs at the exit edge. The fact that the density at the edge may rise above this value for slip less than $1/(n+1)$ is not thought to be serious, as it affects only a small fraction of the stator.

Eqn. (22) of Section 10.1 shows that at a slip of $1/(n+1)$ the flux density at the exit edge is

$$B_x = \frac{\rho_r J_s \pi (n+1)}{p\omega\sqrt{\left[1 + \left(\frac{n+1}{\tau\omega}\right)^2\right]}} (1 + \exp - t_s/\tau) 10^8$$

If the ratio of slot width to slot pitch is k_2, the peak tooth density is $B_x/(1-k_2)$, which after substitution for p gives the flux density (K_2) as

$$K_2 = \frac{\rho_r J_s (n+1) n (1 + \exp - t_s/\tau) 10^8}{4\pi r k_1 f \cos\theta_0 (1-k_2)\sqrt{\left[1 + \left(\frac{n+1}{\tau\omega}\right)^2\right]}} \quad . \quad (13)$$

(5.1.3) Stator Copper Loss and Slot Leakage Reactance

To produce given values of J_s, stator copper loss and slot leakage reactance are interdependent, the deeper the slot the higher the leakage reactance, but the lower the copper loss.

$$\text{The stator resistivity } \rho_s = \frac{\rho_c \text{ (slot pitch)}}{\text{(area of copper section in a slot)}}$$

where ρ_c is the resistivity of copper.

For S slots/pole/phase, the slot pitch in the direction of motion of the field is $2\pi r k_1 \cos\theta_0/3Sn$; the slot area is $2\pi r k_1 k_2 d \cos\theta_0/3Sn$, where d is the slot depth; and the area of copper in a slot is $2\pi r k_1 k_2 k_3 d \cos\theta_0/3Sn$, where k_3 is the packing factor.

Thus the stator copper loss $K_4 = \frac{\frac{1}{2}\rho_s J_s^2}{k_5^2}$ (block area) or

$$K_4 = \frac{2\pi r^2 k_1 \rho_c J_s^2}{k_2 k_3 k_5^2 d} \quad . \quad . \quad . \quad . \quad . \quad (14)$$

It is convenient to assess the slot leakage reactance in terms of the voltage drop it produces relative to the component V_p of the supply voltage in phase with J_s which produces the power output, so that we may write

$$\frac{\text{stator copper loss}}{\text{power output}} = \frac{\frac{1}{2}\rho_s J_s^2 \text{ (block area)}}{\frac{1}{2}V_p J_s \text{ (block area)}} = \frac{\rho_s J_s}{V_p}$$

Writing $k_4 = J_s X_s / V_p$, where $J_s X_s$ is the reactive voltage, then

$$\frac{\text{stator loss}}{\text{output}} = \frac{\rho_s J_s}{J_s X_s} k_4 = \frac{\rho_s k_4}{X_s} \quad . \quad . \quad . \quad . \quad (15)$$

X_s/ρ_s is a quantity which depends only on the geometry of a slot. As illustration, it is simply assumed here that an open slot is completely filled with a matrix of copper and insulation, evenly distributed, so that the slot permeance is $d/3w$, where w is the slot width, whence $X_s = 4\pi \,.\, d \,.\, 2\pi f 10^{-9}/3w$ whilst

$$\rho_s = \frac{\rho_c}{wdk_3} \quad \text{and} \quad \frac{X_s}{\rho_s} = \frac{8\pi^2 d^2 f k_3}{3\rho_c} 10^{-9}$$

Eqn. (15) now gives

$$k_4 = \frac{8\pi^2 d^2 f k_3 10^{-9} K_4}{3\rho_c \,(\text{output})}$$

Curves of output/n (rotor copper loss) are plotted in Fig. 15 against t_s/τ for various values of n for a slip of $1/(n+1)$. It

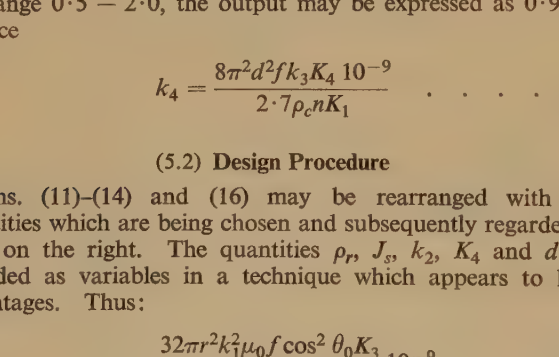


Fig. 15.—Theoretical curves of $\dfrac{\text{output}}{n \times \text{rotor copper loss}}$.

is apparent that, to a first order of approximation, for t_s/τ in the range $0{\cdot}5 - 2{\cdot}0$, the output may be expressed as $0{\cdot}9nK_1$, whence

$$k_4 = \frac{8\pi^2 d^2 f k_3 K_4 \, 10^{-9}}{2{\cdot}7\rho_c n K_1} \quad . \quad . \quad . \quad . \quad (16)$$

(5.2) Design Procedure

Eqns. (11)–(14) and (16) may be rearranged with the quantities which are being chosen and subsequently regarded as fixed on the right. The quantities ρ_r, J_s, k_2, K_4 and d are regarded as variables in a technique which appears to have advantages. Thus:

$$\rho_r = \frac{32\pi r^2 k_1^2 \mu_0 f \cos^2 \theta_0 K_3}{n^3 g} 10^{-9} \quad . \quad . \quad . \quad (17)$$

$$\rho_r J_s^2 = \frac{K_1 k_5^2}{2\pi r^2 k_1 k_\tau} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

$$\frac{\rho_r J_s}{1 - k_2} = \frac{4\pi r k_1 f \cos\theta_0 K_2 \sqrt{\left[1 + \left(\dfrac{n+1}{n\pi} K_3\right)^2\right]}}{n(n+1)(1 + \exp - K_3)} 10^{-8} \quad . \quad (19)$$

$$k_2 d K_4 = \frac{2\pi r^2 k_1 \rho_c J_s^2}{k_3 k_5^2} \quad . \quad . \quad . \quad . \quad (20)$$

$$d^2 K_4 = \frac{2{\cdot}7 k_4 \rho_c n K_1}{8\pi^2 f k_3} 10^9 \quad . \quad . \quad . \quad . \quad (21)$$

The procedure suggested is as follows: The rotor copper loss is fixed for a particular value of r by the number of watts per unit area which can be dissipated by the cooling arrangement. For a machine of given output, the radius is therefore fixed by the fact that the output is nearly n times the rotor copper loss and that n has been chosen by experience*; $\cos\theta_0$ is fixed by the speed range demanded; g is set by considerations of mechanical construction and pole-face losses. By starting from the output and choosing r for maximum dissipation, an attempt is being made to obtain minimum frame size. The remainder of the design is aimed at optimizing the efficiency and minimizing the stator cooling problem. A value of K_3 is chosen. Then ρ_r is calculated from eqn. (17). Having obtained ρ_r, J_s can be calculated, and so on, until eqns. (20) and (21) remain with only d and K_4 as variables. Solution of this pair of equations for K_4 completes the first run. Now K_3 is changed and a repeat calculation indicates the trend in K_4. Then K_3 is varied until K_4 is a minimum. This minimum value is either acceptable or not as regards heating or efficiency. If it is unacceptable, n, r and K_1 are the parameters which may be changed.

The theory which would enable power factor to be predicted is incomplete. In the absence of an exact formula the expression

$$\frac{\int_0^{np} B_q ds}{\int_0^{np} B_p ds} + k_4 = \left[1 + \frac{\rho_s}{\rho_r}\right] \tan\zeta$$

is a rough guide, where the integrals represent the areas under the B_p/distance and B_q/distance curves respectively, and $\cos\zeta$ is the power factor. Substituting for B_p and B_q at $\sigma = 1/(n+1)$ from eqns. (2) and (3) and integrating yields

$$\tan\zeta = \frac{a_0(a_0^2 + \pi^2) - (a_0^2 - \pi^2)(1 + \varepsilon^{-a_0})}{\pi[a_0^2 + \pi^2 - 2a_0(1 - \varepsilon^{-a_0})](1 + \rho_s/\rho_r)} + \frac{k_4}{1 + \rho_s/\rho_r}$$

(5.3) Mechanical Construction

In specific designs due account should be taken of the unusual mechanical loading in a short-stator machine. To this end a calculation of $(B_p^2 + B_q^2)$, which is proportional to the magnetic force per unit area between rotor and stator, is shown in Fig. 16

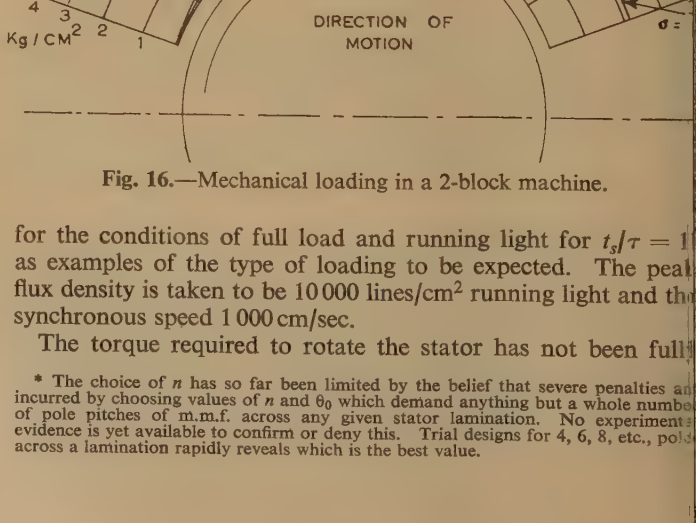


Fig. 16.—Mechanical loading in a 2-block machine.

for the conditions of full load and running light for $t_s/\tau = 1$ as examples of the type of loading to be expected. The peak flux density is taken to be 10 000 lines/cm² running light and the synchronous speed 1 000 cm/sec.

The torque required to rotate the stator has not been full

* The choice of n has so far been limited by the belief that severe penalties are incurred by choosing values of n and θ_0 which demand anything but a whole number of pole pitches of m.m.f. across any given stator lamination. No experimental evidence is yet available to confirm or deny this. Trial designs for 4, 6, 8, etc., poles across a lamination rapidly reveals which is the best value.

investigated, but experiment has shown that its maximum value is about 40% of the full-load torque. A small pilot motor driving the stator shaft via a worm gear is considered to be a suitable arrangement.

(5.4) Rotor Construction

The interconnected conducting matrix of the rotor presents a special problem of its own. For small machines the obvious solution is a cast-aluminium rotor. For larger sizes the rotor conducting grid is probably easier to fabricate than to cast. The experimental rotors so far constructed were wound with tinned copper wire in both directions, together with wires of resin-cored solder. The whole mass was then heated to melt the solder. In larger machines it may be desirable to heat only a small section of the rotor at any one time and perhaps make the joints between bars and rings one at a time. In this case the total number of joints becomes a potent factor in the cost. The machines discussed in Section 4 had 150 rotor slots and 23 rings, making 3450 joints. The rotors were entirely satisfactory from every point of view, and it was decided to build a further rotor for comparison which had only 54 slots and 7 rings (378 joints). The cross-sectional area of copper per centimetre of periphery was the same as before. The main external effect of a reduction in the number of joints was an apparent increase in rotor resistivity, in this case about 33%. Other evidence supporting this view was the reduction in the ratio peak/standstill torque values and the value of slip at peak torque. The other effect was a reduction of power factor, which is thought to be due to a combination of increased rotor slot leakage and zig-zag leakage. This theory is supported by evidence supplied by the stator exit-edge loss, which was about 15% smaller in the case of the rotor with the coarse structure. Increased rotor leakage increases the value of τ_0.

(6) OPERATION AS A GENERATOR

It was pointed out in Reference 2 that the spherical machine could be used as a generator by driving it above the demanded speed. This property could be utilized for such purposes as regenerative braking or for more continuous operation, such as providing a constant-frequency power supply from a variable-speed mechanical source.

Eqns. (2) and (3) may be used to predict the performance at negative values of slip. Table 1 gives a list of some of the

Table 1

DESIGN QUANTITIES

	Motor	Generator
Full-load slip	$\frac{1}{n+1}$	$-\frac{1}{n-1}$
Torque $\times \omega_s$	$(n+1) \times$ rotor copper loss	$(n-1) \times$ rotor copper loss
Torque $\times \omega$	$n \times$ rotor copper loss	$n \times$ rotor copper loss
Efficiency at full-load slip	$\frac{n}{n+1+(\rho_s/\rho_r)}$	$\frac{n-1-(\rho_s/\rho_r)}{n}$

important quantities in the design of a short-stator motor and their corresponding values for the machine used as a generator. The efficiency is lowered when the machine is run as a generator, and the electrical power output as a generator is less than the mechanical output as a motor for the same rotor loss.

(6.1) Experimental Results

The 45° pre-skewed machine was tested as a generator. The results of a load test are shown in Fig. 17, and an experimental flux analysis is shown in Fig. 18. The efficiency as a motor is

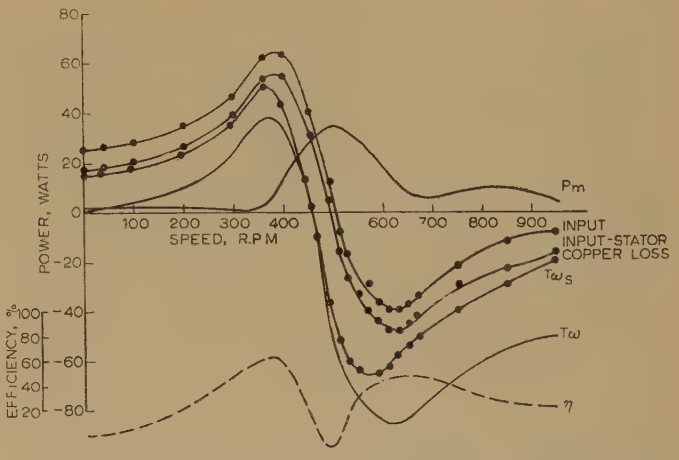


Fig. 17.—Performance curves of a machine used as a generator.

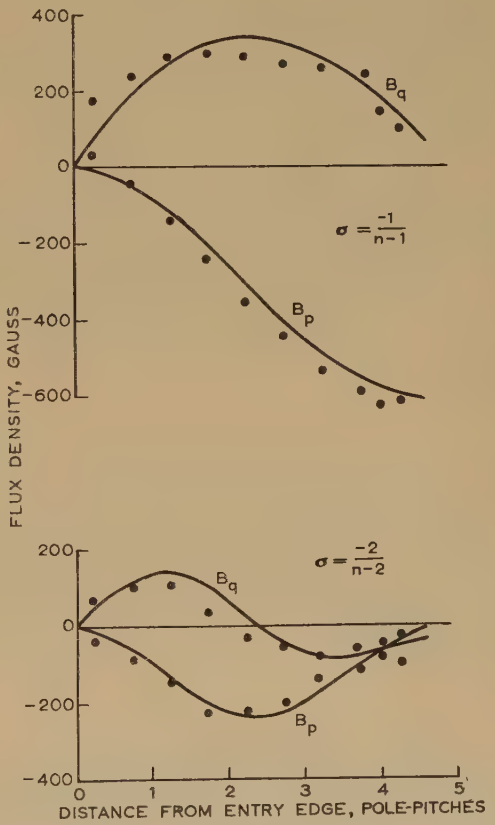


Fig. 18.—Flux distribution under a stator block when generating.

lower than that in the previous tests owing to the use of a larger air-gap. The lines in Fig. 18 indicate the flux distribution predicted by eqns. (2) and (3). Clearly the performance as a generator can be predicted in a similar manner to that for operation as a motor. No detailed design procedure has been

attempted for a machine specifically built for use as a generator, but it appears that for a given output a generator would be slightly larger and have rather more poles than a motor of the same output.

(7) CONCLUSIONS

The main feature of the development work described concerns the design of machines with an angle of pre-skew. The advantages of this type of construction are considerable. The experimental work on the machine with $\theta_0 = 45°$ showed convincingly that the theory developed for this type of machine was substantially correct. It appears that on a 14 in-diameter rotor, a 1·5 : 1 speed range is just about as large as can be obtained with reasonable performance. For larger machines, where n can be increased whilst maintaining an adequate pole pitch, higher speed ranges are clearly possible. The tests on the second machine with a 2 × 2·33-pole block reveal a rather exaggerated feature, which occurs to a lesser extent even in machines of superior design, namely, on a given frame size the best characteristics are not necessarily given by the greatest pole number which gives adequate pole pitch. The technique of designing for $\theta = \theta_0$ at top speed is clearly a good one. The efficiency of the 63½° skew machine, poor though it was, was substantially maintained at reduced angles. The properties of the 45° skew machine at reduced speed were certainly good. The first machine may, in fact, be regarded as a more or less correctly designed machine for 1·4 : 1 range.

Much work remains to be done on the design. The five equations at present used give a broad outlook as to the general effects of changes in various parameters. These equations may conveniently be modified to a 'per unit area' basis as suggested in Reference 4. Factors which have been neglected include rotor leakage, zig-zag leakage, end-turn leakage, and Carter's coefficient, all of which are very difficult to contemplate. The rotor leakage does not contribute any large effect, since the rotors of short-stator machines are of much higher resistivity than their conventional counterparts. Rotor slots in spherical motors tend to be very shallow. Neglect of the other leakages affects the design mostly in respect of the predicted power factor.

(8) ACKNOWLEDGMENTS

The authors wish to express their appreciation of the assistance given them by the Metropolitan–Vickers Electrical Co. Ltd., who provided the material for most of the experimental models. They are also indebted to Mr. Arthur Ashworth of the same company, and to Mr. F. Najmabadi for much useful discussion on design problems, and to Miss C. M. Popplewell for assistance with the computation.

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(10) APPENDICES

(10.1) Evaluation of Torque and Losses

(10.1.1) Rotor Copper Loss.

To simplify the integration the following substitutions are made:

$$a_0 = \frac{n\pi}{\tau\omega(1-\sigma)}$$

$$b_0 = \frac{\pi\sigma n}{1-\sigma}$$

$$c_0 = \frac{1}{\tau\omega}$$

$$x = \frac{s}{np}$$

Eqns. (2) and (3) thus reduce to:

$$B_p = \frac{\rho_r J_s}{u_s}\left(\frac{\sigma}{\sigma^2 + c_0^2}\right)\left[1 - \varepsilon^{-a_0 x}\left(\cos b_0 x + \frac{c_0}{\sigma}\sin b_0 x\right)\right]$$

$$B_q = \frac{\rho_r J_s}{u_s}\left(\frac{c_0}{\sigma^2 + c_0^2}\right)\left[1 - \varepsilon^{-a_0 x}\left(\cos b_0 x - \frac{\sigma}{c_0}\sin b_0 x\right)\right]$$

$$(B_p^2 + B_q^2) = \frac{\rho_r^2 J_s^2}{(\sigma u_s)^2[1 + (c_0/\sigma)^2]}[1 - 2\varepsilon^{-a_0 x}\cos b_0 x + \varepsilon^{-2a_0 x}] \quad . \quad . \quad . \quad . \quad (22)$$

From eqn. (7),

rotor copper loss =

$$\tfrac{1}{2}\rho_r \int_0^{np}\left[J_s^2 - \frac{2J_s g}{4p\mu_0}B_q + \left(\frac{g}{4p\mu_0}\right)^2 (B_p^2 + B_q^2)\right]ds$$

$$= \tfrac{1}{2}\rho_r J_s^2 np - \frac{\rho_r J_s^2 npc_0^2}{\sigma^2 + c_0^2}\int_0^1\left[1 - \varepsilon^{-a_0 x}\left(\cos b_0 x - \frac{\sigma}{c_0}\sin b_0 x\right)\right]dx$$

$$+ \frac{\tfrac{1}{2}\rho_r^2 J_s^2 np}{\tau\omega}\int_0^1 (1 - 2\varepsilon^{-a_0 x}\cos b_0 x + \varepsilon^{-2a_0 x})dx$$

After integration and rearrangement the rotor copper loss is given by

$$\text{rotor copper loss} = \frac{\tfrac{1}{2}\rho_r J_s^2 np}{a_0^2 + b_0^2}\left[b_0^2 + \frac{2a_0 b_0}{a_0^2 + b_0^2}(a_0 \sin b_0 + b_0 \cos b_0)\varepsilon^{-a_0} + \frac{a_0(a_0^2 - 3b_0^2)}{2(a_0^2 + b_0^2)} - \frac{a_0}{2}\varepsilon^{-2a_0}\right] \quad . \quad (23)$$

(10.1.2) Torque.

Rewriting eqn. (8) in terms of a_0, b_0 and c_0,

$$Fu_s = \tfrac{1}{2}\rho_r J_s^2 np\left(\frac{\sigma}{\sigma^2 + c_0^2}\right)\int_0^1\left[1 - \varepsilon^{-a_0 x}\left(\cos b_0 x + \frac{c_0}{\sigma}\sin b_0 x\right)\right]dx$$

$$= \tfrac{1}{2}\rho_r J_s^2 np\frac{a_0}{c_0(a_0^2 + b_0^2)}\left\{b_0 + \frac{\varepsilon^{-a_0}}{a_0^2 + b_0^2}\right.$$

$$\left.[2a_0 b_0 \cos b_0 + (a_0^2 - b_0^2)\sin b_0] - \frac{2a_0 b_0}{a_0^2 + b_0^2}\right\} \quad . \quad . \quad . \quad (24)$$

(10.1.3) Exit-Edge Loss.

Using eqn. (10) and substituting for $B_p^2 + B_q^2$ from eqn. (22) with $x = 1$,

$$P_x \frac{\tau_0}{t_s} = \frac{\frac{1}{2}\rho_r J_s^2 g(1-\sigma)}{u_s 8\pi\mu_0 \frac{t_s}{\tau}(\sigma^2 + c_0^2)}(1 - 2\varepsilon^{-a_0}\cos b_0 + \varepsilon^{-2a_0})$$

$$= \frac{\frac{1}{2}\rho_r J_s^2 np}{2(a_0^2 + b_0^2)(1-\sigma)}(1 - 2\varepsilon^{-a_0}\cos b_0 + \varepsilon^{-2a_0}) \quad . \quad (26)$$

Eqn. (26) is plotted in Fig. 8 for $n = 4$.

(10.2) Velocity Discrepancy for 2-Block Pre-Skewed Construction

At the neutral position each part of the rotor surface crosses the same number of equally-spaced stator slots as it passes under one block. Therefore the slotting is everywhere such as to correspond with constant skew in an equivalent flat machine. This may be alternatively stated as follows:

When the rotor axis is used as the axis of a cylindrical projection in which equal angles of latitude and longitude are plotted as equal distances, the slots appear in this projection as straight lines. With the stator in the central position ($\theta = \theta_0$) the path of any point on the rotor also produces a straight line, since rotor paths are lines of latitude. If the rotor is turned through an angle ϕ with respect to the stator, the projection of the path of a point on the rotor is no longer a straight line. Fig. 19 illustrates the problem.

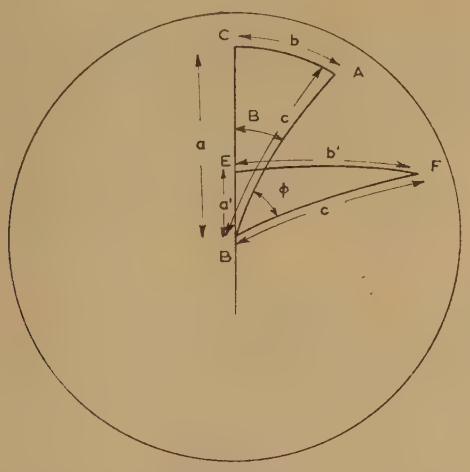


Fig. 19.—The problem of change of spherical axes.

A point A on the rotor is defined by spherical co-ordinates a and b with respect to a point B when the angle $\theta = \theta_0$.

The co-ordinates of this same point after the rotor has been turned through an angle ϕ about axis through B are a' and b'.

Then $\cos c = \cos a \cos b$ from $\triangle$ ABC (27)

$$\frac{\sin B}{\sin b} = \frac{1}{\sin c} = \frac{1}{\sqrt{(1 - \cos^2 a \cos^2 b)}} \text{ from } \triangle \text{ ABC} \quad . \quad (28)$$

$$\frac{\sin(B + \phi)}{\sin b'} = \frac{1}{\sin c} = \frac{\sin B}{\sin b} \text{ from } \triangle \text{ ABC} \quad . \quad (29)$$

$$\cos c = \cos a' \,.\, \cos b' \text{ from } \triangle \text{ BEF} \quad . \quad . \quad (30)$$

Substituting in eqn. (28) the value of $\sin b'$ from eqn. (29),

$$\sin b' = \sin b \cos\phi + \sin\phi \cos b \sin a \quad . \quad . \quad (31)$$

and using eqns. (27), (30) and (31)

$$\cos a' = \frac{\cos a \cos b}{\sqrt{[1 - (\sin b \cos\phi + \sin\phi \cos b \sin a)^2]}} \quad . \quad (32)$$

From eqns. (31) and (32) the projected co-ordinates of a point on the rotor surface can be calculated.

The path of the rotor edges is indicated and the area common to rotor and stator is shown shaded in Figs. 12 and 14.

The problem of calculating the field velocity in the direction of motion of the rotor at any position under the stator block at any angle ϕ is again a problem of two systems of co-ordinates. The problem is illustrated in Fig. 19. For a 45° pre-skew it will be apparent that if an observer starts from B and moves a' degrees along the direction of BE and then b' degrees along the direction of EF he crosses $a' \pm b'$ slots if there is one slot per degree, the sense of the slope of the slots governing the sign of b'. The rate of increase of $a' \pm b'$ with a' at fixed b, which is proportional to the stator field velocity in the direction of the rotor, is therefore $1 \pm \partial b'/\partial a'$. Note that b is fixed because a point on the rotor always moves along a line of latitude. When a point (a', b') on the stator block has been chosen, the latitude b of the point on the rotor which passes under (a', b') when the stator is in the position ϕ is defined by eqns. (31) and (32). The rate of increase of longitude a of this point, i.e. the actual rotor angular velocity, is given by $\partial a/\partial a'$ at fixed b, and the rate at which a point on the rotor cuts the stator slots is given by

$$K = \left(1 \pm \frac{\partial b'}{\partial a'}\right) \Big/ \frac{\partial a}{\partial a'} \quad . \quad . \quad . \quad . \quad . \quad (33)$$

For the Figure as drawn, the sign of $\partial b'/\partial a'$ is negative; this is now used throughout for the sake of clarity.

The latitude b which passes under (a', b') for the position θ is found by solving eqns. (31) and (32) for $\sin b$.

Thus, substituting for $\sin a$ in eqn. (31),

$$\sin b' = \sin b \cos\phi + \sin\phi \cos b \sqrt{[1 - (\cos^2 a' \cos^2 b')/\cos^2 b]}$$

where $\phi = (\theta - \theta_0)$.

This yields the quadratic in $\sin b$ as follows:

$$\sin^2 b - (2 \sin b' \cos\phi) \sin b$$

$$- \sin^2\phi(1 - \cos^2 a' \cos^2 b') + \sin^2 b' = 0$$

Whence $$\sin b = \sin b' \cos\phi$$

$$\pm \sqrt{[\sin^2 b' \cos^2\phi + \sin^2\phi(1 - \cos^2 a' \cos^2 b' - \sin^2 b')]}$$

which reduces to

$$\sin b = \sin b' \cos\phi \pm \sin\phi \sin a' \cos b' \quad . \quad . \quad (34)$$

Consideration of the geometry will show that the relevant sign to the particular problem being studied is the negative one.

From eqn. (31)

$$\cos b' \frac{\partial b'}{\partial a} = \sin\phi \cos b \cos a \quad . \quad . \quad . \quad (35)$$

From eqn. (32)

$$\frac{\partial a'}{\partial a} = \frac{\sin a \cos b \cos^2 b' - \sin b' \cos^2 a \cos^2 b \sin\phi}{\sin a' \cos^3 b'} \quad . \quad (36)$$

From eqns. (35) and (36)

$$\frac{\partial b'}{\partial a'} = \frac{\sin\phi\cos b\cos a\cos^3 b'\sin a'}{\cos b'(\sin a\cos b\cos^2 b' + \sin b'\cos^2 a\cos^2 b\sin\phi)} \quad . \quad (37)$$

Using eqns. (33), (36) and (37)

$$K = \frac{\sin a\cos b}{\cos b'\sin a'} - \frac{\sin b'\cos^2 a\cos^2 b\sin\phi}{\cos^3 b'\sin a'} - \frac{\sin\phi\cos b\cos a}{\cos b'}$$

Substituting for $\sin a\cos b$ from eqn. (31), for $\cos a\cos b$ from eqn. (32), and for $\sin\phi$ from eqn. (34) and simplifying,

$$K = \tan b'\sin\phi\sin a' + \cos\phi - \sin\phi\cos a'$$

For given values of ϕ and K, this is the equation of the line of constant slip over the stator block.

By scaling K so that its value at $x = 0$, $y = 0$ is unity, lines of constant γ can be drawn as defined in Section 4.1.2. These are plotted for a 45° pre-skew in Figs. 12(*a*) and 12(*b*) for $\theta = 33°$ and 57°.

If the angle of pre-skew is not 45°, eqn. (33) is modified to read

$$K = \left(c \pm \frac{\partial b'}{\partial a'}\right) \Big/ \frac{\partial a}{\partial a'}$$

where c is the number of lines of longitude crossed per line of latitude by a point moving along a slot. For a 63½° pre-skew, $c = \frac{1}{2}$. The plotted values of γ for $\theta = 27°$ for a 63½° pre-skewed block are shown in Fig. 14.

DISCUSSION ON

'APPLICATION OF A VARIABLE-REACTOR/CAPACITOR COMBINATION FOR REVERSING AND CONTROLLING THE SPEED OF POLYPHASE INDUCTION MOTORS'*

Mr. E. De Baets (*Belgium: communicated*): In the paper it is shown that the locus of I_p at standstill is a circle on a chord O′S; the torque is proportional to O′X (Fig. 4). This is a special case of a more general property: when an external impedance

$$Z_e = Z_e\varepsilon^{j\phi_e} = R_e + jX_e$$

is introduced in one of the supply lines of a 3-phase induction

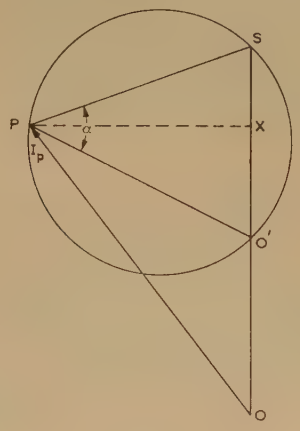


Fig. A

motor, the locus of I_p at standstill is a circle (Fig. A) including on the chord O′S an angle

$$\alpha = \pi - |\phi_s - \phi_e|$$

ϕ_s being the angle of the motor impedance per phase at standstill:

$$Z_s = Z_s\varepsilon^{j\phi_s} = R_s + jX_s$$

When ϕ_e is negative or positive but smaller than ϕ_s, the circle lies on the left of O′S; when ϕ_e is positive and greater than ϕ_s, on the right. The torque remains proportional to O′X. It can be proved without difficulty that the ratio of the magnitudes of Z_e and Z_s is

$$\frac{Z_e}{Z_s} = \frac{1}{2}\frac{\text{PS}}{\text{PO}'} \text{ or } \frac{3}{2}\frac{\text{PS}}{\text{PO}'}$$

according as the machine is Δ- or Y-connected.

When Z_e is a pure reactance jX_e, the circle becomes that of Fig. B (corresponding to circle I_p of Fig. 4); the arc O′P′S

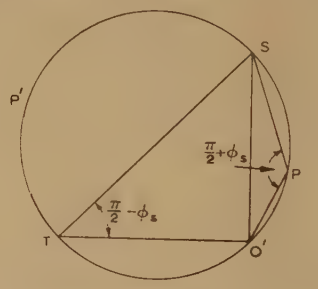


Fig. B

relates to capacitance; the arc OPS to inductance. In this case the torque is zero at point O′, where PO′ = 0; hence $Z_e = \infty$ and at point T, where (for a Δ-connected machine)

$$\frac{Z_e}{Z_s} = \frac{1}{2}\frac{\text{TS}}{\text{TO}'} = \frac{1}{2\sin\phi_s} \text{ or } Z_e = \frac{R_s^2 + X_s^2}{2X_s}$$

and not $R_s^2/2X_s + X_s^2/Z_s$ as indicated in the paper. The value of $Z_e = -X_e$ is also found by equalizing at zero the difference $I_p^2 - I_n^2$:

$$R_s^2 + (X_s + X_e)^2 - X_e^2 = 0$$

Prof. T. V. Sreenivasan (*in reply*): I thank Mr. E. De Baets for pointing out the error in treating $X_s^2/2X_s$ as X_s^2/Z_s. I also thank him for the interesting theoretical contribution that at standstill the locus of I_p is a circle as long as the argument of Z_e is constant.

* SREENIVASAN, T. V.: Paper No. 2697 U, October, 1958 (see 105 A, p. 522).

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AN ELECTROMAGNETIC VARIABLE-RATIO TORQUE CONVERTOR

By D. O. BISHOP, Ph.D., B.Sc.(Eng.), and G. S. BROSAN, Ph.D., B.Sc.(Eng.), Members.

(*The paper was first received 28th October, and in revised form 17th December, 1958. It was published in April, 1959, and was read before the* UTILIZATION SECTION *16th April, 1959.*)

SUMMARY

The torque convertor differs radically from any other type known to be in commercial use. It depends for its operation upon the phenomenon exemplified in Faraday's disc and constitutes, theoretically, an 'infinitely variable' gear whose ratio can be varied over a wide range.

This paper is limited to a brief description of the basic principles and some details of the experimental results obtained from tests on a simple model.

LIST OF SYMBOLS

I = Current in main circuit.
Φ_1 = Total flux linking rotor 1.
Φ_2 = Total flux linking rotor 2.
I_1 = Current in exciting coil for rotor 1.
I_2 = Current in exciting coil for rotor 2.
V_1 = E.M.F. induced in rotor 1.
V_2 = E.M.F. induced in rotor 2.
N_1 = Speed of rotor 1.
N_2 = Speed of rotor 2.
T_1 = Torque applied to rotor 1.
T_2 = Torque applied to rotor 2.
R = Resistance of main current path.
ω = Angular velocity of a rotor.
v = Linear velocity of a point in a rotor.
r = Distance of a point from shaft axis.
B = Flux density at a point in one rotor.
δs = Length of an element in one rotor measured in the direction in which the e.m.f. acts.
K = Constant.

(1) INTRODUCTION

There are a number of ways of transmitting power from one rotating shaft to another so that the torque ratio and/or the speed ratio can be varied smoothly. Electromagnetic methods of doing this suffer from the disadvantage that the machines required are usually bulky and/or inefficient. For example, if the input power is transformed into electrical power by the conventional type of d.c. generator, and is then fed to a conventional d.c. motor, the desired effect is achieved, but the equipment is too large and heavy for many purposes. Again, if the power is transmitted via a rotary magnetic field (for example, if the input shaft drives a rotary d.c. field system, which, in turn, drives a squirrel-cage winding on the output shaft), speed-ratio variation can only be obtained by permitting losses to occur, and torque conversion is not possible.

The device described in the paper will permit power transmission with smooth control over speed ratio and torque ratio. With suitable development the machine can be made relatively small and light, and is ideally 100% efficient at all times. The device has been called the conduction drive.

Dr. Bishop is at Watford Technical College and was formerly in the Electrical Engineering Department, The Polytechnic, London.
Dr. Brosan is at Willesden Technical College.

(2) PRINCIPLES

(2.1) Basic Construction

The torque convertor consists basically of a homopolar generator coupled to a homopolar motor, the two being in close proximity under a common housing. A simplified form of construction is shown in Figs. 1 and 2.

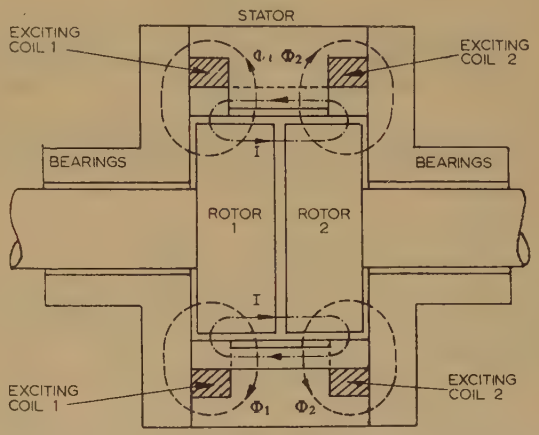


Fig. 1.—Diagram showing main components of the torque convertor and the general directions of the magnetic flux and current paths.
The gaps between rotors and stator are not drawn to scale.

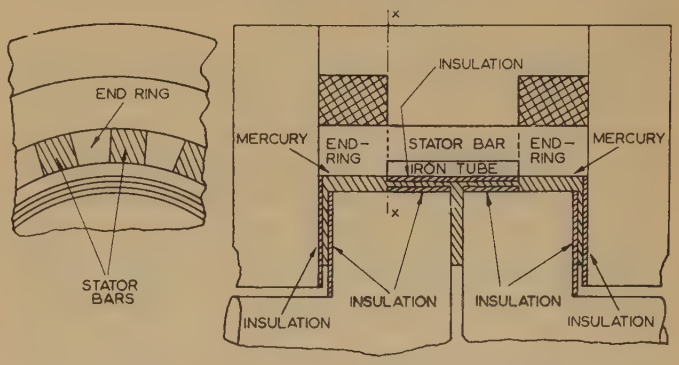


Fig. 2.—The main constructional details of the torque convertor.
The left-hand diagram is a section at XX.

Two solid cylindrical rotors, made of high-permeability material, are connected to input and output shafts, respectively, and housed in a stator. The gaps between the rotors and between each rotor and the stator, radially and axially, are fairly small (of the order of 0·015 in). The stator is also made of high-permeability material. It houses two exciting coils, as shown in Fig. 1, and a copper squirrel-cage winding comprising two end-rings connected by bars running axially, as shown in Fig. 2. An iron tube lies inside the squirrel cage but does not

extend beyond the end-rings. The housing is completed by two end-plates, which contain mercury seals and bearings capable of taking both axial and radial thrusts.

The inside surfaces of the stator and end-plates, and the surfaces of the rotors, are covered with a thin layer of insulating varnish with the exception of (*a*) the inner face of each end-ring, (*b*) the part of each rotor surface immediately opposite the end-rings, and (*c*) the adjacent faces of the rotors.

The spaces between the rotor and the stator are filled with mercury.

(2.2) Simplified Theory of Operation

When direct currents, I_1 and I_2, are fed into the exciting coils, magnetic fluxes Φ_1 and Φ_2 are set up in the stator and rotors as shown. The flux density in each rotor will, of course, vary in both radial and axial directions, but in the first instance this non-uniformity will be ignored.

When rotor 1 is driven at a speed N_1, an e.m.f.

$$V_1 = K\Phi_1 N_1$$

will be induced therein. A current I will thus flow through the stator squirrel cage, rotor 2 and rotor 1 via the mercury in the gaps.

The current I, together with the flux Φ_2 linking rotor 2, produces a torque on rotor 2, and it will rotate if free to do so. It is clear that

$$\frac{T_1}{T_2} = \frac{\Phi_1 I}{\Phi_2 I} = \frac{\Phi_1}{\Phi_2}$$

Thus any desired torque ratio (positive or negative) may be obtained by varying the magnitudes and/or directions of the exciting currents I_1 and I_2.

The speed ratio will be influenced by the losses occurring in the machine. If the generated e.m.f. is

$$V_1 = K\Phi_1 N_1$$

the back e.m.f. generated in rotor 2 is

$$V_2 = K\Phi_2 N_2$$

Then

$$V_1 - V_2 = IR$$

from which the ratio N_1/N_2 may be determined if all other losses are ignored.

(3) MORE RIGOROUS THEORETICAL TREATMENT

(3.1) Flux, E.M.F. and Current Distribution

In each rotor the flux density is far from uniform, and the current path has a large widely-varying cross-section. Thus it is not possible to determine the exact current distribution by analytical methods. However, some simplification is possible as follows:

Consider an element at point X (Fig. 3) at a radius r. If ω is the angular velocity of the rotor, the linear velocity of the element is $v = \omega r$ so that an e.m.f. will be induced in the element

$$Bv\delta s = B\omega r\delta s$$

The magnetic flux linking the element is

$$\delta\Phi = B2\pi r\delta s$$

Thus

$$\delta V = \frac{B\omega r\delta s}{B2\pi r\delta s}\delta\Phi$$

or

$$\delta V = \frac{\omega}{2\pi}\delta\Phi$$

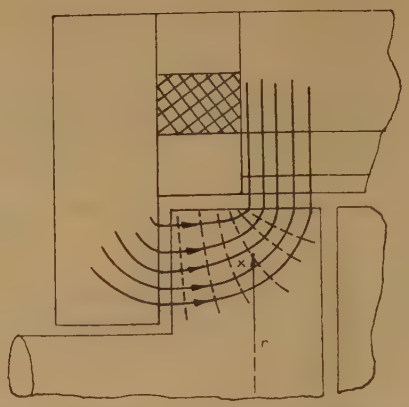


Fig. 3.—Diagram illustrating the derivation of the e.m.f. equation.

The full lines represent part of the magnetic flux linking the rotor. The dotted lines are orthogonal to the magnetic lines of force and give the directions of the e.m.f.'s acting in the rotor.

Thus the total e.m.f., V, induced in the rotor is

$$\int dV = \int \frac{\omega}{2\pi} d\Phi = \frac{\omega}{2\pi}\Phi$$

$$= \frac{\omega}{2\pi} \times \text{Total flux linking the rotor}$$

In other words, V is independent of the distribution of the magnetic flux, but is directly proportional to its magnitude.

It is possible to draw an 'e.m.f. field' (as shown in Fig. 3) which is orthogonal to the magnetic field. Were it not for the resistance of the rotor, this would give the directions of current flow at all points. It may be useful, however, as a first approximation.

Thus, although the equations $V_1 = K\Phi_1 N_1$ and $V_2 = K\Phi_2 N_2$ are substantially correct, R is merely an equivalent value and may vary appreciably as the current distribution changes.

(3.2) Armature Reaction

The path of the current I is a single-turn toroid and it sets up an m.m.f. acting in a circumferential direction. Were it not for saturation effects, this m.m.f. would not affect the induced e.m.f. However, it can be shown that, even when the rotor iron is fully saturated in a circumferential direction, it is possible to obtain reasonable variation in the component of flux density which lies axially-cum-radially (i.e. the component which determines the magnitude of the e.m.f.).

Nevertheless, it is desirable to reduce the effect of the m.m.f. of I, and this may be done by inserting in each rotor one or more radial non-magnetic inserts, to increase the reluctance in a circumferential direction.

(3.3) Losses

(3.3.1) I^2R Losses.

By suitable design the I^2R losses may be made very small, the limiting factor being, in most cases, the weight of the machine. It is thought that the losses due to any contact resistance between the mercury and iron or copper are negligible. The copper squirrel cage in the stator (Fig. 2) has been inserted solely for the purpose of reducing the stator resistance, and squirrel cages could be used for this purpose in the rotors but other factors may make it undesirable.

(3.3.2) Iron Losses.

If the flux density in the gaps between the rotors and the stator is uniform in a circumferential direction, there will be no iron

losses in the machine. This can be seen from the fact that around any closed path in the rotors the e.m.f. is zero, provided that there is no time variation of the flux. On the other hand, if axial copper bars are inserted in the stator and/or the rotor, flux pulsations, and consequently iron losses, will occur in nearby regions of the stator and/or rotor due to reluctance changes. It is a simple matter to reduce this effect to a negligible value by 'closing the slots'. In the example of Figs. 1 and 2 this has been done by inserting an iron tube in the stator.

(3.3.3) **Mechanical Losses.**

In addition to the frictional losses at the bearings, there will be losses due to the viscosity of the mercury. With laminar flow and a uniform velocity gradient across the gap, the mechanical losses in the mercury would be quite tolerable because its viscosity (0·015 poise) is quite small. Turbulence will inevitably occur and cause a substantial increase in loss. This is most likely to occur in the regions by the outer adjacent edges of the two rotors.

However, this is not solely a hydrodynamic problem. The mercury is an electrical conductor, and, as it moves in a magnetic field, currents are induced in it, and both hydrodynamic and electromagnetic forces act. Let us consider, for example, the mercury around the periphery of a rotor adjacent to the stator insulation. Whereas the hydrodynamic forces alone tend to produce a uniform velocity gradient, the electromagnetic forces will tend to make all the mercury in this region rotate with the same angular velocity as the rotor. When both forces act simultaneously, the bulk of the mercury will probably rotate at an angular velocity almost as great as that of the rotor, and there will be a steep velocity gradient on the stator side of the gap. The effect will be to reduce the gap very considerably and so increase the viscosity losses. Furthermore, the electromagnetic forces in the mercury adjacent to the copper end-rings will tend to make it remain stationary. This probably increases the velocity gradient near the rotor surface and also creates turbulence in the region by the inner edge of the end-ring, where the electromagnetic forces have the former tendency.

The problem is receiving attention and is being investigated analytically and experimentally.

(3.3.4) **Leakage Current Losses.**

Even if the stator and rotor insulating films are sound enough to prevent leakage currents from flowing in the stator, such currents must flow through the mercury at the periphery of each rotor. Fortunately, the effect (mentioned in Section 3.3.3) which causes the mercury to rotate with the rotor also tends to reduce the leakage current to a minimum, since that portion of the mercury which rotates with the rotor is, electrically, part of the rotor and has induced in it e.m.f.'s tending to produce current which contributes to the main current I.

The problem is bound up with that mentioned in Section 3.3.3 and is being investigated with it.

(4) AN EXPERIMENTAL MODEL

(4.1) Construction

A model of the form shown in Figs. 1 and 2 was constructed and tested. The stator and rotors are solid and of low-carbon steel. The stator squirrel cage was formed by machining the stator and casting-in high-conductivity copper. The inner faces of the stator and the rotors were nickel-plated to resist any electrochemical action with the mercury. The stator and rotor insulation was insulating varnish applied with a brush and subsequently baked.

Each rotor shaft runs in a pair of tapered roller bearings to prevent axial movement under the considerable end thrusts which exist when in operation. High-quality carbon seals are fitted to each shaft near the rotor.

The overall dimension of the stator is 14 in, and each rotor is 7½ in in diameter and has an axial length of 3 in. Each exciting coil consists of 1 000 turns and can safely carry a current of 1·5 amp continuously.

(4.2) Experimental Results

The open-circuit e.m.f. was measured by removing one end-plate and rotor, and touching probes on the periphery of one rotor and its shaft. The e.m.f. was 0·7 volt at 1 500 r.p.m. with full excitation. The machine was fully assembled and tested with various excitations and loads, and the following observations were made.

The maximum overall efficiency obtainable was 45% with an output of 3·1 h.p., input and output speeds of 1 000 and 700 r.p.m., respectively, and currents of 1·0 amp in each of the exciting coils.

The separate losses for this test were calculated to be of the following order:

I^2R loss in main current circuits	1·6 kW
Mechanical losses including all losses in mercury and leakage losses (if any)	1·1 kW
Iron losses	80 watts

The effective resistance of the main current circuit was estimated to be 4×10^{-6} ohm, a figure somewhat higher than the design value. Thus a current of the order of 20 000 amp was flowing.

In general, the machine behaved as expected with regard to speed-ratio variation, and smooth variation was possible over a wide range. The response to rapid exciting-current changes was good. In the extreme case the output exciting current was reversed rapidly by a switch, and the output rotor slowed down and accelerated to full speed in the reverse direction in about 6 sec.

(5) CONCLUSIONS

One of the main causes of the relatively low efficiency is the unexpectedly large 'mechanical' loss in the mercury, and it is considered that this will be reduced to a low value when steps are taken to minimize turbulence.

The I^2R losses in the main current circuit were also larger than expected. A possible explanation is that the shapes of the electric and magnetic circuits do not permit the maximum current flux linkages, with the result that the 'effective' resistance of the main circuit is higher than the calculated value (see Section 3.1). Another possibility is that the current density over some cross-sections of the circuit varies over a wider range than was anticipated. However, it is considered that the above losses can be reduced considerably by suitable design.

The ease and smoothness with which the torque ratio can be varied show that it will be possible to build a machine which can perform functions not possible with any other of comparable size, weight and efficiency.

(6) ACKNOWLEDGMENTS

The authors wish to express their gratitude to Mr. F. S. Schroeder of Lancashire Dynamo Holdings, Ltd., for his encouragement and assistance, and also to Mr. R. T. Sutton of Lancashire Dynamo and Crypto, Ltd., for his invaluable help and advice on production methods.

[The discussion on the above paper will be found overleaf.]

DISCUSSION BEFORE THE UTILIZATION SECTION, 16TH APRIL, 1959

Dr. W. J. Gibbs: Can the authors give, in more detail, the field of application of the convertor? They seem to assume, in the Introduction, that it can be made to operate satisfactorily for quite large powers, but I doubt this.

The basic construction in Figs. 1 and 2 shows that they have exercised much ingenuity in overcoming difficulties. The mean flux path is shown to cross two air-gaps, one of which must be comparatively large. But the large air-gap can be shunted by a path through the roller bearings, so that more than half the working flux will pass through the bearings unless non-magnetic rings are inserted between the end-plates and the bearings.

The theoretical treatment is open to criticism. I believe the authors' concepts are inappropriate. We should not think of e.m.f.'s and currents in this connection, but of voltage gradients and current densities. The concept of an 'e.m.f. field', in particular, is an unhappy one. Even if the mathematics were acceptable, it simply tells us that the total e.m.f. induced in the rotor is proportional to the total flux braking the rotor for a given speed. I suggest that the authors consider different concepts such as the wave-impedance one.*

A conventional designer will be surprised to find that, according to the authors, the armature m.m.f. is ten times the excitation m.m.f. It is not a true armature reaction since it has no effect on the main field. However, the m.m.f. from the current of 20 kA acts on a path of inherently low reluctance, and we should expect that a large number of the radial non-magnetic inserts mentioned by the authors would be needed.

The low efficiency cannot be attributed mainly to the turbulence in the mercury, because it would only rise to 59% even if the mechanical losses could be entirely eliminated. The authors give no indication of how much torque is contributed by the mercury drag. It would be disconcerting to find that most, if not all, of it were transmitted in that way.

The authors point out that the hydrodynamic and electromagnetic effects are closely related, and each reacts on the other. Probably the only rigorous treatment of such a system is to set up appropriate tensor equations. The principal difficulties would then lie in establishing the parameters of the system. Such equations might help considerably towards the perfection of this convertor by indicating the exact interrelation of effects and what losses are avoidable. No doubt the mathematics would be difficult, but such a theoretical analysis would be well worth undertaking.

Mr. C. J. Carpenter: The authors have made a very simple and compact device, but it is essentially a motor-generator set, and is therefore bound to be large and heavy in relation to its power rating. The model confirms this. It is interesting to speculate whether there is fundamentally any advantage in size to be gained by using the homopolar instead of an appropriately-designed heteropolar arrangement. The output coefficient of homopolar machines is not inherently large, and the simplicity is, to some extent, offset by the disadvantages of mercury brushes.

The main feature of the test results is the 1·6 kW I^2R loss. It would appear that a better balance between magnetic and electric requirements could be obtained by adding a rotor 'winding', i.e. a series of radial copper inserts. These might improve the magnetic as well as the electric performance, since, with a current of 20 kA, the armature reaction effect is evidently such as to produce complete saturation of the iron unless a circumferential air-gap is included. It is not stated in the paper whether non-magnetic inserts were included. This is one of several important details of the model and of the tests which have been omitted.

The title of Section 3 is hardly appropriate. The result which is obtained in Section 3.1 can be written down by inspection, and the remainder of the discussion is entirely qualitative. The voltage induced in a conductor moving through a constant magnetic field is given by the flux cut per second; since the flux cut per revolution is Φ the e.m.f. is $(\omega/2\pi) \times \Phi$. The authors' use of the word 'linkage' is misplaced since Φ does not link the rotor, nor does $\delta\Phi$ link the element.

The 'e.m.f. field' referred to in Section 3.1 is evidently the induced electric field, and I am puzzled by the authors' avoidance of the term. They remark, 'Were it not for the resistance of the rotor, this (field) would give the directions of current flow at all points'.

In fact, the resultant electric field (and therefore the current vector) in the rotor may correspond approximately to the induced field when the resistivity is sufficiently *large*, but not when it is small.

A less obvious objection to the authors' statement is revealed by a more detailed analysis of the machine. The current vector must be continuous,

i.e. $$\operatorname{div} \boldsymbol{J} = 0$$

whereas this is not true of the induced electric field. The two fields cannot therefore be similar. The induced field is given by

$$\boldsymbol{E}' = \boldsymbol{u} \times \boldsymbol{B}$$

from which

$$\operatorname{div} \boldsymbol{E}' = \boldsymbol{B} \,.\, \operatorname{curl} \boldsymbol{u} = 2\omega B$$

This field is not given by Maxwell's equations, and it is essentially for this reason that homopolar induction has been widely regarded as anomalous. Under the influence of this field the disc acquires a charge of one sign distributed around the periphery, combined with an opposite charge distribution throughout its volume. This is the only circumstance in which a static electric charge distribution is not confined to the surface of a conductor.

When the electric field which the charges produce is added to the induced field the result is zero. Current flow in the mercury and the stator is due entirely to these static charges, and the current, in turn, modifies the charge distribution in such a way as to cause current flow in the rotor. The resultant electric field in the rotor bears no direct relationship to the induced field. Fortunately it satisfies Laplace's equation (whereas the induced field does not) and is therefore easily solved by any of the methods available for Laplacian fields. However, the potential difference between any two points (including points on the surfaces) will not be given by the authors' expression for the e.m.f.

Mr. A. S. Fenemore: There is a strong axial thrust due to flux entering or leaving the ends, and it is possible to consider a design in which this is avoided. If the rotor is extended axially, flux can be arranged to enter and leave only from the curved surface of the cylinder, and then only radial magnetic forces will exist.

Plates of copper can be inserted in the rotor in axial planes, and connected along the top edges in a manner similar to the end ring on the squirrel-cage motor. This reduces the resistance in the main circuit. The containing slots are closed by iron bridges only where flux enters or leaves the rotors, to avoid the flux pulsations mentioned by the authors. Furthermore, the iron bridges reduce considerably the reluctance of the air-gaps. Another advantage is that the circumferential reluctance of the

* CULLEN, A. L., and BARTON, T. H.: 'A Simplified Electromagnetic Theory of the Induction Motor, Using the Concept of Wave Impedance', *Proceedings I.E.E.*, Monograph No. 283 U, January, 1958 (105 C, p. 331).

successive plates of copper will considerably reduce the toroidal flux, due to excitation from the current of 20 kA.

The efficiency of the model, i.e. 45%, is disappointing. This low efficiency means large losses, which involves a cooling problem. It has a bearing, too, on the contact resistance between the mercury and the current-carrying surfaces. The authors have assumed this contact drop to be negligible.

If we remove one end-plate, and feed in current from an external source, it should be possible to measure the contact drops. It would be necessary to use a null method, or to ensure that the measuring probes do not themselves introduce a contact drop.

For long-term operation, it should be considered whether there is risk of mercury oxidation at the operating temperatures from air diffusing in through the seals. Any contamination of the mercury will lower the efficiency still further. A recent paper* describes good results using nickel-plating followed by rhodium-plating.

The device needs to be filled with a metal which is liquid at room temperature or below, the only choice being mercury or a sodium-potassium alloy. A eutectic mixture of sodium and potassium melts at $-11°C$, which would be suitable from that aspect. It has the advantages of lower resistivity, and, more important, lower viscosity, both being only about one-third of the corresponding values for mercury. Because both constituents have a strong affinity for oxygen, the alloy is a good cleaning agent, removing any oxide films and giving negligibly low contact resistance. This same property means a very rigid exclusion of air, and a double-sealing arrangement would be necessary, with an inert gas maintained between the seals. This arrangement could be used with mercury, if oxidation of the latter occurs.

The subject of magnetohydrodynamics has received some consideration in a recent report.† This also gives references to earlier work on magnetohydrodynamics.

For the speeds at which the device will be used, there will be considerable turbulence in the mercury. This is likely to affect the insulation on the rotor and stator surfaces, and appreciable erosion may result unless the material is very good indeed. The test results are limited to one particular running condition, with a statement of efficiency. Curves of the actual performance are desirable.

Mr. J. G. W. West: I regard this as a homopolar Ward Leonard set rather than a Faraday disc. A possible heteropolar design has been mentioned, but this must, of course, be a Ward Leonard set.

With the high currents involved in the machine, it can almost be called an 'educated short-circuit'. A current of 20 kA seems colossal. However, the current density is low, and it is actually less than that of a conventional d.c. machine.

I consider it very important that the circuit for the current in the rotor should be copper bars arranged in a way similar to that on the stator.

A possible method of reducing the large magnetohydrodynamic losses in the mercury would be to localize the mercury to areas where the magnetic flux density is low, e.g. between copper end rings on both rotor and stator. It may be possible to hold the mercury in position by surface tension.

Axial air-gaps are unsatisfactory for two reasons: the axial pull of the rotors has to be taken by the bearings, and axial gaps usually have to be greater than radial gaps for manufacturing reasons. The return gap could quite easily be a radial one.

The torque convertor may be suitable for two applications that interest me; first, as an automotive transmission of, say, 60 h.p. output at an input speed of 3000 or 4000 r.p.m., and secondly, as a constant-speed drive for an aircraft alternator of, say, 50 kVA running at 8000 or 12000 r.p.m. and driven from an engine with a 3 : 1 speed range. What would be the approximate weight, size and efficiency of torque convertors for these two applications?

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Drs. D. O. Bishop and **G. S. Brosan** (*in reply*): In reply to Dr. Gibbs and Mr. West on the question of fields of application, the factors involved are similar to those for other machines. We have not, up to the present, found any factor limiting the power which can be transmitted by this means, and the power/weight ratio increases considerably with the linear dimension. On the reasonable assumption that losses can be reduced to give efficiencies of about 85%, the weight of the magnetic and electric circuits (i.e. excluding the weight of bearings, cooling auxiliaries, etc.) for a 60 h.p. convertor could be less than 100 lb for a machine designed for 4000 r.p.m., and possibly below 30 lb for one designed for 12000 r.p.m.

Mr. Carpenter raised some interesting points relating to the theory of operation of the machine, and these are of importance when considering how to obtain the best flux and current distributions, because, when this is done, the I^2R losses will be substantially reduced. If all parts of the electric circuit (including the stator) are of the same material the current distribution for a given induced electric field ('e.m.f. field') will depend solely on the shape of the electric circuit and will be independent of the resistivity. As Mr. Carpenter states, the potential difference between any two points will not be given by our expression for the e.m.f., but nevertheless, as a first approximation, the induced electric field (e.m.f. field) indicates the directions of current flow. The situation is not as simple as he postulates. The principal difference is that the motion of the mercury sets up e.m.f.'s in both axial and radial directions, and these influence the current distribution in the critical part of the machine, namely the mercury layer. We do not wish at this stage to enter into a discussion on flux cutting and flux linking. But where is the 'conductor' to which Mr. Carpenter refers? A proof similar to ours but with constant flux density is given in a well-known textbook.*

We do not think the 'wave-impedance' concept suitable as it is only appropriate for heteropolar machines. A detailed study of the exact position in the machine using, in part, tensor analysis is in hand. However, our first concern is to deal with the engineering of the problem, and the analysis must therefore wait until the geometry of the device is finalized. We have also drafted test procedures enabling the machine parameters to be determined under various conditions.

The whole of the working flux does, in fact, pass through the two air-gaps; these need not be large in practice. Insulating inserts, which are in any case necessary, stop flux passing through the end-plates and bearings.

As Mr. West states, the magneto-hydrodynamic forces could be reduced by confining the mercury to a region where the flux density is low. The reduction in the amount of mercury would also reduce the viscous drag. We doubt, however, whether

* WATT, D. A.: 'The Development and Operation of a 10 kW Homopolar Generator with Mercury Brushes', *Proceedings I.E.E.*, Paper 2606 U, June, 1958 (105 A, p. 233).

† WATT, D. A.: 'Analysis of Experimental D.C. Pump Performance and Theory of Design', A.E.R.E. Report Ref. R/R2275.

* CARTER, G. W.: 'The Electromagnetic Field in its Engineering Aspects' (Longmans, Green, 1954). pp. 169–170.

surface tension alone would keep the mercury in position. Additional rubbing seals would be required and extra friction losses would be introduced.

In reply to the several suggestions that copper bars should be inserted in the rotors, this has, in fact, been done.

With regard to Dr. Gibbs's suggestion that the torque may be transmitted by viscous drag, we must confess that, when testing an earlier model, the same thought occurred to us. But we reversed one of the exciting currents and discovered that the machine transmitted power almost as well with one rotor rotating in the opposite direction to the other.

We should like to thank Mr. Fenemore for his suggestions about rhodium plating and the use of eutectic sodium-potassium alloy. These are very interesting and will be pursued, although our method for sealing would be unsuitable for a liquid conductor other than mercury. We have experienced no difficulty over counteracting the end-thrust of the rotors.

The advantage of the machine over conventional heteropolar motor-generator sets is compactness and the large specific loading factors possible. The advantages of the homopolar machine are the comparative simplicity of construction, including the absence of windings other than simple magnetizing coils. Design studies for larger machines show very considerable advantages.

DISCUSSION ON 'ELECTRICITY IN MODERN COMMERCIAL HORTICULTURE'*

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 15TH DECEMBER, 1958

Mr. S. Littlewood: There is a system of space heating for glasshouses in which polythene tubing is employed. Have the authors any knowledge of this system, and if so, would they give their observations?

Much has been said in the paper about the use of electricity for space heating in glasshouses. Will the authors give some idea of the load at which electricity as the heating medium becomes uneconomic?

Mr. A. Stewart: The authors draw attention to the value of electricity for producing crops early in the season. Will they comment on the practicability of producing crops late in the season to meet the market at a time when prices start to rise after the peak of the season?

Recent reports indicate that the total area of heated glasshouses is decreasing. Is this purely due to high fuel costs?

Mr. J. K. Hulme: The paper refers to soil sterilization by electricity, but compared with steam sterilization, the electrode type of sterilizer was considered to give inferior results. Growers need reassurance that the E.R.A. contact-heating sterilizer does not suffer from the same defects as the electrode sterilizer.

Reference has been made in discussion to a prejudice existing in the minds of growers towards electrical equipment, but it is doubtful whether such a prejudice exists. Reluctance to install new electrical equipment arises from economic consideration. The staff of the N.I.A.E. inform growers whether it is more economic to employ various items of electrical equipment, and close liaison between the N.I.A.E. and the E.R.A. is likely to lead to more definite advice being passed on to growers.

Messrs. C. A. Cameron Brown and **A. W. Gray** (*in reply*): There is indeed electrical space-heating equipment for glasshouses using polythene tube. The basic equipment is either an electric heater bank or an oil-fired boiler for the larger installations (up to 500 000 B.Th.U.), the warm air being distributed through perforated polythene tube by means of a fan. The polythene tube is laid at floor level through the crop, the warm air issuing at quite a slow rate through the perforations in the immediate vicinity of the plant. A considerable advantage of this equipment is that, even when heating is not required, great benefit is derived from running the fan and circulating air through the crop, and, in so doing, assisting with the very difficult problem of ventilation, particularly during the summer months.

The problem of the economic use of electricity for space heating in glasshouses is not primarily one of load but of temperature. While, in general, electrical space heating is not economical for large blocks of glasshouses, except where frost protection only is required, it can be economic for propagating houses, where the closeness of control of temperature is essential.

Mr. Stewart.—Electricity is, of course, already in use for producing crops later in the season than normal, and an outstanding example of this is in the use of electric lighting for delaying the flowering of mid-season and late chrysanthemums. It could also be used for delaying a number of other crops, although this is not at present a commercial practice.

The total area of heated glasshouses is decreasing slightly each year. This is not due entirely to high fuel costs, but to the fact that, while all production costs are increasing each year, the price of horticultural produce remains static. The consequence of this is that the poorer type of glasshouse, badly sited and with poor light value, is being used just to give protective cover against the weather to a crop grown cold, instead of for intensive production using heat.

Mr. Hulme.—A basic objection to the electrode type of sterilizer is that the results vary with the type of soil to be sterilized. With a medium loam and a correct moisture content, quite satisfactory sterilizing can be carried out with the electrode sterilizer. With a light sandy soil, which will hold little moisture, it is difficult to get sufficient current flow to raise the soil to sterilizing temperature, while with a heavy clay with a high moisture content the current flow is often such as to blow fuses. The E.R.A. contact-heating type of sterilizer does not suffer from this disadvantage, inasmuch as it works on the conduction of heat from the heated plates into the soil. Therefore, the electrical resistance of the soil does not enter into it, and almost any medium can be satisfactorily raised to a temperature of 180° F, which is sufficient for pasteurization.

We agree that there is nowadays very little prejudice existing in the minds of growers towards electrical equipment and that it is not so much a reluctance to install new electrical equipment which slows up progress as a shortage of capital. It is gratifying to note, however, that many growers are now finding that the economic benefits of electrical equipment on their holding are so great that it is essential to provide such equipment, even though it means taking up loans through the bank to do so. We agree that close liaison between the N.I.A.E., the E.R.A. and the whole of the electrical industry is essential to demonstrate the advantages of electricity to the commercial grower.

* Cameron Brown, C. A., and Gray, A. W.: Paper No. 2272 U, January, 1957 (see 104 A, p. 249).

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AN ALTERNATOR WITH FIELD-FORM ENVELOPE CONTROL

By J. W. PANNELL, M.Sc.(Eng.), Associate Member.

(*The paper was first received* 10*th April, and in revised form* 10*th June*, 1959.)

SUMMARY

Consideration is given to a method of waveform synthesis by changing the generated waveform envelope as an alternative to the more usual procedure in which the desired non-sinusoidal waveform is obtained by mixing selected constituent harmonics. A rotating machine is used and continuous variation of the shape of the generated waveform may be made with the machine in motion.

A preliminary version of this apparatus has been constructed from a modified induction motor, but owing to the inherent heteropolar form of the magnetic circuit, this machine will synthesize only waveshapes containing the odd harmonic series.

For convenience in observation and measurement a fundamental frequency of 50 c/s has been selected for the prototype, but with suitable modification of the magnetic circuits, higher frequencies and also waveforms containing both odd and even harmonic series could be obtained.

(1) INTRODUCTION

In a conventional form of single-phase alternator, one of the normal requirements is the production of a voltage waveform of sinusoidal shape.

Normally, when a non-sinusoidal waveform is required, the constituent harmonic frequencies are generated by means of individual alternators or oscillators and then combined together in some suitable manner,[1] but the particular form of alternator described here makes it possible to vary the voltage waveform envelope while the machine is running, by means of the special arrangements provided for field excitation. An early application of field-form modification was used in rotary convertors by Woodbridge.[2]

The present synthesizer has an exciting coil on each stator tooth of a modified induction motor so that variation of the air-gap flux density is possible over the whole periphery of the air-gap. The rotor is wound with a single non-chorded coil in which is induced a rotational e.m.f. having, in the ideal case, the same waveform as that of the flux distribution.

Oscillograms traced from photographs of some possible waveforms are shown in Fig. 1, the change from one to another being made with the machine in motion. The absence of even harmonics is due to the inherent heteropolar form of construction of the machine.

A selector switch, having pre-set values of excitation, is provided to give an instantaneous change of waveform and, for normal use, potential dividers may be connected for each magnetic axis and calibrated in terms of per-unit maximum generated waveform amplitude.

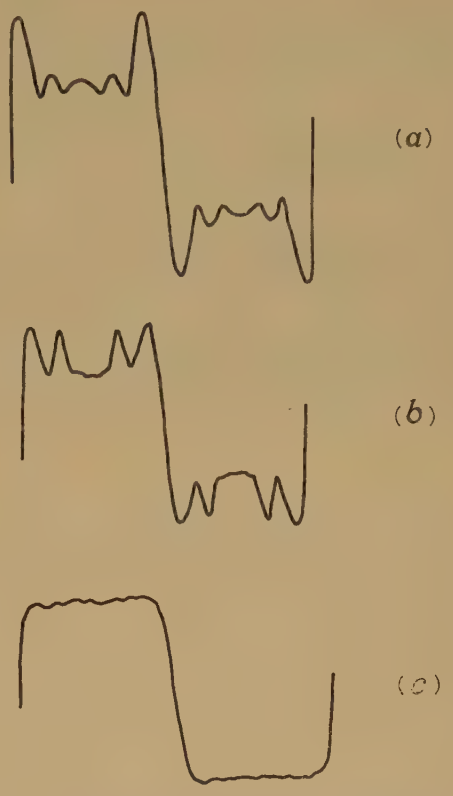


Fig. 1.—Induced voltage waveforms, as synthesized.

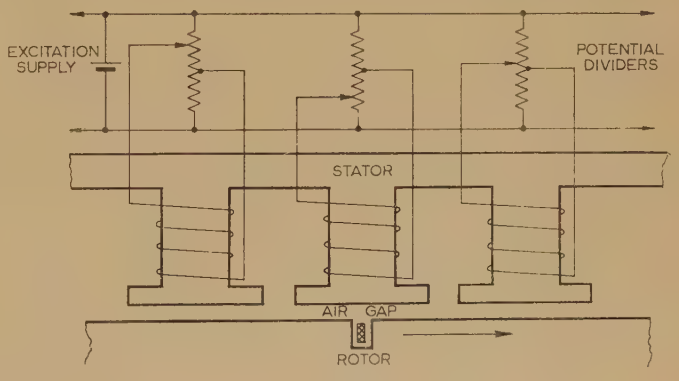


Fig. 2.—Basic excitation circuit.

(2) DESCRIPTION OF THE ALTERNATOR

The original windings were removed from a small induction motor and a coil was wound on each of the 24 stator teeth. A 2-pole one cycle per revolution arrangement was chosen and diametrically opposite stator coils were connected in series to give 12 magnetic axes. Each coil pair was then supplied with an adjustable direct-current excitation with provision for a choice of polarity, as shown in Fig. 2.

The rotor die-cast winding was also removed and replaced by a full-pitch coil connected to slip-rings, suitable brush gear being provided. After preliminary experiments it was found desirable to return the rotor stampings to their original skewed state of one stator-slot pitch in order to reduce the generated ripple.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Mr. Pannell is in the Department of Electrical Engineering, Derby and District College of Technology.

The synthesizer was driven at 3 000 r.p.m. by a synchronous motor to give a fundamental output frequency of 50 c/s; other driving speeds would give correspondingly different fundamental frequencies.

(3) OPERATION

Various waveforms, such as those shown in Fig. 1, were set up in turn using calculated values of excitation for each of the magnetic axes and allowing for the magnetic characteristics of the core material.

Subsequent harmonic analysis from the oscillograms showed that the expected harmonics were present, with approximately the predetermined amplitudes. A certain amount of slot ripple was observed, as can be seen in the rectangular type of waveform, Fig. 1(*c*).

A more suitable method of operation is to adjust the excitations until the required waveform is produced on an oscillograph.

(4) CONCLUSIONS

Experimental work with the apparatus demonstrated the feasibility of this method of waveform synthesis, which obviates the need for synchronization of the individual harmonics normally necessary with other methods.

The use of only 12 magnetic axes imposes rather severe limitations on the fidelity with which a desired waveform can be copied and a larger number will therefore be incorporated in future apparatus.

One application for the apparatus is the harmonic analysis of waveforms; the excitations are adjusted until the synthesized waveform coincides with that under analysis, using an oscillograph for comparison. The required values of mid-ordinates are then obtained from the calibrated excitation controls.

At present the equipment is used in connection with investigations into certain aspects of commutation in electrical machines.

(5) ACKNOWLEDGMENT

The experimental work described was performed at the then Northampton Polytechnic, London, as part of the research programme.[3] The author wishes to acknowledge the encouragement and assistance received from Dr. P. F. Soper, Head of the Department of Electrical Engineering.

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PROGRESS IN PERMANENT-MAGNET MATERIALS

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SUMMARY

The most widely used permanent-magnet materials are at present the field-treated alloys, cast or sintered, of nickel, aluminium, cobalt and iron. Practice and theory have worked together to obtain, in the best of these alloys, an assembly of aligned single-domain shaped particles in which a very high proportion of the intrinsic magnetization is retained after removal of a magnetizing field and also against high reverse fields. Ceramic-like ferrite magnets have higher coercivity but lower remanence, and the development of these can also be linked with domain theory. Many other alloy materials continue to be used in a limited sphere, but future progress is likely to be linked with the preparation of iron or iron-cobalt particles in elongated single-domain form and the manufacture of permanent magnets from aligned compacts of such particles, as indicated by recent experimental work.

LIST OF SYMBOLS AND UNITS

H = Field strength, oersteds.
H_c = Coercivity—field strength to reduce induction from remanence to zero, oersteds.
H_{ic} = Intrinsic coercivity—field strength to reduce magnetization to zero, oersteds.
B = Induction, gauss.
B_i = Intrinsic magnetization, gauss.
B_r = Remanence—induction at zero field after previous saturation, gauss.
$(BH)_{max}$ = Maximum value of the product of BH in the demagnetizing quadrant of a hysteresis loop, megagauss-oersteds.

The paper discusses and evaluates materials in the units of the C.G.S. system. For the M.K.S. system, the following variations and conversions should be noted:

Magnetization, $M = (B - \mu_0 H)$, Wb/m^2.
10 000 G = 1 Wb/m^2.
$4\pi \times 10^{-3}$ oersted = 1 A/m.
40π gauss-oersteds = 1 J/m^3.

Note also that the maximum available energy per unit volume of a permanent-magnet material is $(BH)_{max}/8\pi$ ergs/cm^3 with $(BH)_{max}$ in gauss-oersteds and $(BH)_{max}/2$ with $(BH)_{max}$ in joules per cubic metre.

(1) INTRODUCTION

A useful reference point for this review of progress is the similar review made eleven years ago,[1] in which were described the high-energy anisotropic materials based on field-treated alloys of nickel, aluminium, cobalt and iron which had recently become available. Since then, the position of these alloys has been consolidated, so that the major part of the world requirements for permanent magnets is now met by these anisotropic alloys. In the same period there have been improvements in the properties obtainable from commercial supplies of the alloys, marked increases in the best recorded properties and a much better, although not yet complete, understanding of the underlying mechanism. Both improvements and the understanding owe much to the development of the domain theory of magnetization changes and the associated theory of coercivity. This theory and some of the experimental work associated with it have been recently reviewed by Brailsford.[2]

Stimulated by the same theoretical work, there has been much development effort on widely different materials, such as micropowder iron and iron-cobalt, manganese-bismuth and magnetically 'hard' ferrites. The technical and economic limits on these developments are still difficult to predict, but at present only the ceramic-like magnets based on barium ferrite show signs of wide commercial use.

In this review, the characteristics of the available magnet materials of each broad class will be dealt with in approximately their present order of commercial importance, with a short glance at the increasing number of special materials with interesting technical properties but limited usage due to economic factors.

(2) ANISOTROPIC ALLOYS OF NICKEL, ALUMINIUM, COBALT AND IRON

The prototype for the most widely used permanent-magnet material is a cast alloy containing about 13% nickel, 8% aluminium, 24% cobalt, 3% copper, and the balance iron. Small amounts of impurities or deliberate additions such as sulphur, silicon, niobium, tantalum, titanium and zirconium are allowable and may give small advantages, but carbon must be not more than 0·03% unless a special addition has been made to nullify its effect. Such an alloy has an intrinsic saturation magnetization of about 14 000 G, but remanence, coercivity and the general shape of the hysteresis loop are changed considerably by the precise heat treatment to which the alloy is subjected. In particular, if it is cooled from 1 250° C or more to 500° C or lower at a mean rate of about 1 deg C/sec and subjected to a magnetic field of over 1 000 oersteds in at least the range 850–750° C, room-temperature measurements will give an extremely square hysteresis loop in the axis of the field heat treatment, with remanence about 13 000 G and coercivity about 200 oersteds. By prolonged tempering of the alloy in the range 600–550° C, the coercivity increases to 600–800 oersteds, dependent on precise composition, and the high remanence and square loop are almost entirely retained. Measurements in directions perpendicular to that of the field treatment give a lean hysteresis loop with remanence about 4 000 G and coercivity 400 oersteds. Permanent magnets of this general type, with $(BH)_{max}$ values of 5 MG-oersteds or more, are extensively manufactured as Alcomax II, III or IV, Ticonal C or G in this country, Alnico V or VI in the United States, Alnico 500 in Germany, Magnico in the Soviet Union and under somewhat similar names in a number of other countries.

Each manufacturer holds individual views on the merits of the minor additions, but in general niobium (or tantalum) increases coercivity with a small reduction in remanence and $(BH)_{max}$, and also nullifies the harmful effects of the inevitable small residue of carbon; titanium gives even greater increases of coercivity but with more marked reduction of remanence

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and $(BH)_{max}$; and silicon and zirconium reinforce the loop squareness but with a reduction of coercivity. The applications of anisotropic magnets of this class have steadily increased in number because of the undoubted advantage of cost per unit of magnetic energy whenever the overall magnetic circuit design could be adapted to use a simple, compact shape with length and cross-section suitable for utilization of the full $(BH)_{max}$.

The experimental and theoretical work directed to a fuller understanding of the anisotropic alloys has itself led both to improvements in the available properties and to a greater confidence in the utilization of magnets. Investigations by many workers have built up a coherent picture, but the most widely accepted view is largely based on the work of Nesbitt, Heidenreich and Williams.[3, 4] The alloy is a solid solution at high temperatures, but breaks down at about 800° C into a strongly magnetic phase within a weakly magnetic matrix; the magnetic precipitate forms as elongated rods or plates along (100) crystallographic planes. When a magnetic field is applied over the temperature range 850–750° C in which this precipitate is forming, the elongated growth is suppressed in planes nearly perpendicular to the field axis. The use of the field and the optimum cooling rate give a structure in which the elongated precipitate is oriented at an angle between the field axis and the nearest [100] crystal axis. Subsequent tempering to produce maximum coercivity at room temperature appears to cause growth of the precipitate along the crystal axis and also diffusion changes in the composition of the precipitate and matrix.[5, 6]

Quite early in the course of these and other investigations a means of further improvement became clear. The square-loop anisotropic properties are dependent on the correct orientation of the precipitate along the axis of measurement. In the alloy as normally sand cast there is a random grain structure, so that, in individual grains, there can be divergences of up to 54° between a chosen field axis and the nearest [100] cube edge; by utilizing the well-known effect of the growth of columnar crystals from the chilled face of a solidifying casting, this divergence can be greatly reduced with consequent improvement in the anisotropy. The possible benefits of a columnar cast structure appear to have been realized independently by several different workers.[7–10] By casting into moulds with one face of high thermal capacity and the remaining walls of heated, low-thermal-conductivity material, $(BH)_{max}$ values of 7–8 MG-oersteds were realized, with remanence values up to 98% of the intrinsic saturation and coercivity some 20% better than for the random-grain castings. The manufacturing technique involved is not easy for a range of sizes and shapes in mass production, but the columnar form is commercially available in limited sizes as Columax or Ticonal GX in this country.

On simple compact castings, such as the cylindrical slugs used for loudspeaker magnets, a marked proportion of columnar structure can be formed by the use of metal chills in cold sand moulds, and an economical improvement in properties is obtained.[11] Such 'semi-columnar' or 'directional-grain' castings are available as Alcomax II s.c. and III s.c. in this country and Alnico V d.g. in the United States.

Mention has been made of the effect of niobium and titanium additions to the anisotropic nickel-aluminium-cobalt alloys in increasing coercivity with some loss of remanence, and of the effect of $(BH)_{max}$ in random-grain material. It seems probable that both these additions improve the crystallographic form of the precipitate, so increasing coercivity, but cause the precipitate axis to coincide with the crystallographic axis, so reducing remanence and loop squareness in the random-grain casting. Controlled grain orientation should therefore eliminate the latter point, and it has been found that the best $(BH)_{max}$ values obtainable from columnar niobium-bearing alloys are somewhat higher (8·6 MG-oersteds) than from niobium-free alloys. Titanium, as normally added, has the unfortunate secondary effect of grain refining, so that no columnar structure can be obtained from alloys with titanium by the usual techniques, apparently owing to the larger number of non-metallic nuclei on which solidification commences. Luteijn and de Vos[12] have succeeded in preparing a single crystal of an alloy containing 5% titanium, by adopting special refining techniques for the raw materials, and in causing solidification by slow withdrawal from the melt under an argon atmosphere. With the appropriate field treatment, they have obtained a $(BH)_{max}$ of 11 MG-oersteds, the highest yet recorded for any permanent-magnet material. The technique used does not suggest that commercial production of such values will be possible, although the same alloy in the random-grain form has had limited usage for special purposes, with a coercivity of 1 200 oersteds and $(BH)_{max}$ of 4·0 MG-oersteds (Ticonal K, Alnico 350).

In the foregoing review of the anisotropic alloys we have dealt exclusively with cast material, but essentially the same alloys can be formed by powder metallurgy and sintering techniques, followed by heat treatment as for the cast material to produce permanent magnets. The advantage of the sintering technique lies in the more economic production of very small pieces to rather greater precision than by sand-casting procedure; this advantage vanishes as weight increases owing to the much higher cost of powdered raw materials compared with normal melting stock. Sintering can be carried out at temperatures of about 1 350° C, either in dry hydrogen or in vacuum, although the vacuum process has been gaining in recent years. The objective of the sintering process is to produce an alloy of the same composition, structure and density as the cast material, and the final properties are different only to the extent that this objective is not attained. The common deficiency is on density, as it is difficult to eliminate completely the residual porosity caused by starting with a powder compact. This porosity acts both as a reduction of effective cross-section, therefore giving reduced induction values, and also as an effective internal reluctance, therefore giving a shearing effect on the demagnetization curve. The latter is particularly important in its effect on the square-loop anisotropic material, so that sintered alloys with 5% residual porosity, a normal value, will have a $(BH)_{max}$ about 15% less than that for the cast alloy of the same composition and heat treatment.

The grain structure of sintered pieces is usually much finer than that of cast pieces and is completely random in orientation. There is consequently no incidental benefit from a partially columnar structure, such as frequently arises in small sand castings, although the same fine and random-grain structure may be distinctly beneficial to the brittle mechanical properties of the alloy. Attempts have been made to coarsen the structure of sintered alloys to control crystal axes to give a columnar structure,[13] but there has been no commercial development of the method.

Field-hardened anisotropic magnets, cast or sintered, random or partially columnar, now supply the major part of the world's need for permanent magnets. The metallurgical structure of precipitate and matrix is essentially an array of elongated single-domain particles with a high degree of alignment between particles axes and the preferred magnetic axis. Fig. 1 shows how the demagnetization curve changes, for the same alloy and thermal treatment, by application of a magnetic field during cooling and then by the use of material with aligned grain structure; the square loop of curve (*c*) is a close approximation to the theoretical expectation from an aligned assembly of identical single-domain particles.

In Table 1 are listed the most widely used alloys of this general

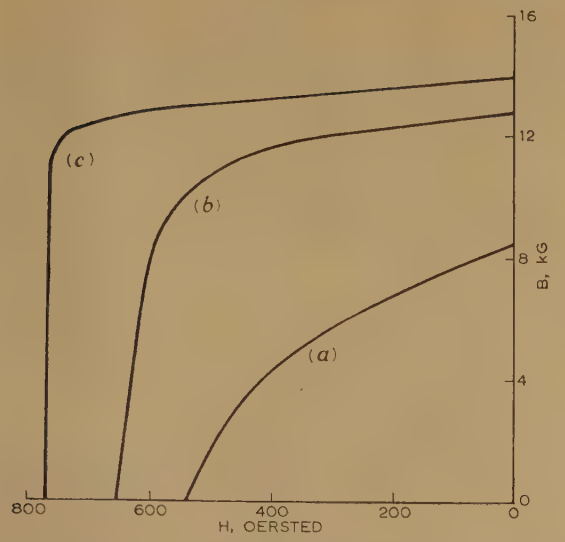


Fig. 1.—Effect of field treatment and grain structure on demagnetization curve for alloy of composition 14% Ni, 7·5% Al, 25% Co, 3% Cu, 0·7% Nb, balance Fe, cooled from 1250° C and tempered at 590–560° C.

(*a*) Random grains—no magnetic field in heat treatment, $(BH)_{max}$ = 1·75 MG-oersteds.
(*b*) Random grains—heat treated in field, $(BH)_{max}$ = 5·4 MG-oersteds.
(*c*) Columnar grains—heat treated in field, $(BH)_{max}$ = 8·7 MG-oersteds.

of strength after magnetization, have been shown to be less for these materials than for most other available types.[16]

(3) ISOTROPIC ALLOYS BASED ON NICKEL, ALUMINIUM AND IRON

The magnet alloys based on nickel, aluminium and iron, but with reduced or zero cobalt content, behave metallurgically in the same way as the anisotropic alloys already considered, but the application of a magnetic field during heat treatment becomes less effective as the cobalt content is reduced, owing to the reduction of the Curie temperature of the strongly magnetic phase to below the temperature at which it nucleates. From an ingenious study of the variation of torque curves with field in single crystals of an iron-nickel-aluminium alloy (Fe_2NiAl), Nesbitt, Williams and Bozorth[17] were able to demonstrate that the coercivity of these alloys is essentially due to the shape anisotropy of a precipitate lying along mutually perpendicular crystallographic planes.

A wide field of application for isotropic magnets still continues where the magnet is in a form in which the strong field necessary for development of anisotropic properties cannot be easily applied along the correct path. The most widely used compositions have continued without change in the last ten years, and are given, together with the normal magnetic properties, in Table 2. The stability of permanent magnets in these alloys has been compared with other materials by the author.[16]

Table 1

TYPICAL ANISTROPIC MAGNET ALLOYS BASED ON NICKEL, ALUMINIUM, COBALT AND IRON

Grain structure	Designation	Composition	B_r	$(BH)_{max}$	H_c
		(Weight % balance Fe)	G	MG-oersteds	oersteds
Aligned	Columax	13·5 Ni 8 Al 24 Co 3 Cu 1 Nb	13 500	7·8	750
	Ticonal GX	13·5 Ni 8 Al 24 Co 3 Cu	13 500	7·5	720
Part aligned	Alcomax II s.c.	11·5 Ni 8 Al 22 Co 4 Cu	12 800	5·15	600
	Alcomax III s.c.	13·5 Ni 8 Al 24 Co 3 Cu 1 Nb	13 000	5·8	700
	Alnico 5 d.g. (U.S.)	13·5 Ni 8 Al 24 Co 3 Cu	13 300	6·5	725
	Ugimax 600 (F)	13·5 Ni 8 Al 24 Co 3 Cu	13 500	6·4	700
Random	Alcomax II	11·5 Ni 8 Al 22 Co 4 Cu	12 400	4·7	585
	Alcomax III	13·5 Ni 8 Al 24 Co 3 Cu 1 Nb	12 500	5·1	670
	Alcomax IV	13·5 Ni 8 Al 24 Co 3 Cu 2·5 Nb	11 200	4·3	750
	Ticonal C	13·5 Ni 8 Al 24 Co 3 Cu 1 Nb	12 500	5·0	680
	Ticonal G	13·5 Ni 8 Al 24 Co 3 Cu	13 480	5·7	583
	Ticonal K	14 Ni 7 Al 34 Co 4 Cu 5 Ti	9 000	4·0	1 100
	Alnico 5 (U.S.)	13·5 Ni 8 Al 24 Co 3 Cu	12 700	5·5	650
	Alnico 6 (U.S.)	15 Ni 8 Al 23 Co 3 Cu 1 Ti	10 500	3·65	760
	Alnico 7 (U.S.)	18 Ni 8·5 Al 24 Co 3 Cu 5 Ti	7 200	2·8	1 000
	Alnico 500 (G)	14 Ni 8 Al 24 Co 3 Cu 0·5 Ti	12 500	5·0	650
	Alnico 350 (G)	15 Ni 7·5 Al 30 Co 4 Cu 5 Ti	8 500	3·8	1 100

(F), French; (G), German; (U.S.), American; others British.

type, with their commercial designations and claimed magnetic properties. Since the basis of the statement of magnetic properties varies with different manufacturers, a close comparison cannot be made, but the main groups are clear, columnar-grain, partially columnar-grain, in which good properties depend on favourable geometric proportions, and random-grain castings, the latter including a group with additions to give particularly high coercivity at the expense of $(BH)_{max}$. The metallurgical structure of such alloys is stable at temperatures between at least −100 and 500° C, and the magnetic changes are small and largely predictable in the same temperature range.[14, 15] The effect of stray fields and vibration, and also the small time changes

Both cast and sintered forms are in use, and, for the isotropic alloys, there is no benefit from a partially columnar structure and residual porosity has less effect on the shape of the demagnetization curve, so that the difference in magnetic properties between the cast and sintered products is small.

(4) STEELS

The martensitic alloy steels, based on iron-carbon with additions of one or more of the elements, chromium, tungsten, cobalt and molybdenum, continue to be used in commercially important quantities of permanent magnets, although this

Table 2

TYPICAL ISOTROPIC PERMANENT-MAGNET ALLOYS BASED ON NICKEL, ALUMINIUM AND IRON

Designation	Composition	B_r	$(BH)_{max}$	H_c
	Weight %, balance Fe	G	MG-oersteds	oersteds
Alni Alnico III (U.S.) Alni 120 (G) Nial (F)	22–27 Ni 11–13 Al 0–3 Cu 0–1 Ti	5 000–6 600	1·25	680–480
Alnico Reco 3A Alnico II (U.S.) Alnico 160 (G) Nialco 12 (F)	16–22 Ni 10 Al 12–14 Co 3–6 Cu 0–1 Ti	6 500–8 000	1·7	670–500

(F), French; (G), German; (U.S.), American; others British.

usage decreases year by year. These materials have mechanical advantages over the nickel-aluminium-iron alloys for some applications in that they can be rolled and forged and that they can be drilled and machined with moderate ease prior to hardening. No significant technical progress in the magnet steels can be reported, but re-design for the newer alloys has been slow in those applications in which the basic material cost is low compared with the manipulative cost in forming the magnetic circuit. The most widely used materials are listed in Table 3.

Table 3

PERMANENT MAGNET STEELS

Designation	Composition	B_r	$(BH)_{max}$	H_c
	Weight %, balance Fe	G	MG-oersteds	oersteds
35% Co steel	35 Co 6 Cr 5 W 0·9 C	9 000	0·95	250
15% Co steel	15 Co 9 Cr 1·5 Mo 1·1 C	8 200	0·62	180
9% Co steel	9 Co 9 Cr 1·5 Mo 1·1 C	7 800	0·50	160
3% Co steel	3 Co 9 Cr 1·5 Mo 1·1 C	7 200	0·35	130
2 Co, 4 Cr steel	2 Co 4 Cr 0·6 W 1 C	9 800	0·32	80
6% W steel	6 W 0·4 Cr 0·7 C	10 500	0·30	65
Cr steel	3–6 Cr 0·9 C	9 800	0·28	70

(5) CERAMIC OR OXIDE MATERIALS

The original non-metallic permanent magnet is, of course, the natural lodestone, or magnetite, with the composition of ferrous ferrite ($FeOFe_2O_3$). There was some development of an oxide material based on cobalt ferrite ($CoOFe_2O_3$), which resulted in limited manufacture under the names Vectolite and Caslox I, described in a previous review.[1] In 1952, Went *et al.*[18] described a new permanent-magnet material of low remanence but exceptionally high coercivity based on a barium ferrite ($BaO6Fe_2O_3$), and there has since been voluminous technical and patent literature on this and similar materials, of which only a few examples need be mentioned here.

If ferrous oxide and barium oxide (or carbonate) are heated to 1 000° C or more, a magnetic compound of hexagonal crystal structure is formed, as first observed by Forestier.[19] As detailed by Went,[18] this compound has a density of 5·3 g/cm^3, a saturation magnetization of about 4500 G and a high uni-axial crystal anisotropy constant. It is an example of the numerous uncompensated antiferromagnetic or ferrimagnetic compounds found in recent years (see Reference 2). The high crystal anisotropy and relatively low saturation magnetization indicate immediately the possibility of high intrinsic coercivity from crystal particles of a size suitable for single-domain magnetic behaviour.

From a random assembly of such uni-axial single-crystal particles there should be obtainable a high-coercivity magnet with a remanence of half the saturation magnetization; if the assembly can be produced with aligned crystal axes, a remanence approaching the saturation magnetization and a square demagnetization curve with high $(BH)_{max}$ should be obtainable in the axis of alignment. The reconciliation of experimental values for coercivity, anisotropy and saturation with domain theory and the variation of these values with temperature have been the subject of useful studies by Rathenau, Smit and Stuyts,[20] by Stuijts, Rathenau and Weber[21] and in the United States by Sixtus, Kronenberg and Tenzer.[22]

Turning now to the production of useful permanent magnets, the usual procedure with the isotropic material is to mix intimately ferrous oxide with a little more than the theoretical quantity of barium carbonate, to compact the powder to the desired form by the known techniques with the aid of small additions of lubricant and bond, and to fire the compact to a temperature of 1 200–1 300° C in a process which combines the formation of the compound crystal growth to an optimum size and densification to about 90% of the theoretical solid density. The firing and densification involve a linear shrinkage of about 17%, with consequent difficulty in precise size control, and the result is a brittle black ceramic of high electrical resistivity.

For anisotropic material more subdivision of these processes is necessary, and it is usual to pre-fire the mixture to give an aggregate containing crystals of greater than single-domain size, followed by a controlled ball milling to give a powder of 1–2 μ mean particle size. A compact of the required shape must be produced from the powder while applying a sufficiently strong magnetic field to produce particle alignment in the ultimate magnetization axis, and alternative procedures using either wet slurries or pre-magnetized dry powders are favoured by different manufacturers. The firing is carried out generally as for isotropic compacts but is rather more critical, as the improvement in properties is more marked as optimum densification is approached; the collapse in properties due to over-firing, excessive grain size and consequent low coercivity can be catastrophic. It is a characteristic of the anisotropic material that the ratio of remanence to saturation and the loop fullness continue to increase on firing into the region where coercivity is rapidly decreasing.

The two main grades of barium-ferrite magnets are commercially available with magnetic properties as in Table 4 in this country and elsewhere. Some care is necessary in considering the available properties and possible applications. The high coercivity and low induction values lead to appreciable differences between the B/H curve and the curve of intrinsic magnetization, B_i, against H. The latter is more fundamental for understanding

Table 4

BARIUM-FERRITE PERMANENT-MAGNET MATERIALS

Designation	B_r	$(BH)_{max}$	H_c
	G	MG-oersteds	oersteds
Caslox II Feroba I Magnadur I Oxit 100 (G) Koerox 100 (G)	2 100	1·0	1 750
Feroba II Magnadur II Oxit 300 (G) Koerox 300 (G)	3 800	3·0	1 700

(Composition, closely $BaO6Fe_2O_3$; density, about 5 g/cm³.)
(G), German; others British.

the domain process in the material, but the former is required for circuit design. Fig. 2 shows typical curves of both kinds for the isotropic and the anisotropic materials. It will be seen that intrinsic coercivity is much greater than normal induction coercivity for the isotropic ferrite, although the difference is small for the anisotropic. There is a practical consequence of some importance for temperature stability. As with other materials in which coercivity is dependent on the crystal anisotropy, there is a marked reduction of coercivity at low temperatures while magnetization increases. Consequently, a cooling cycle causes an irreversible magnetization loss in a permanent magnet with the working point on the portion of the demagnetization curve which is reduced by cooling; this condition applies to anisotropic, but not to isotropic material at $(BH)_{max}$. It is possible to change the firing conditions for anisotropic material so as to maintain a high intrinsic coercivity, but with some reduction in $(BH)_{max}$, and so reduce the losses.[23] The normal reversible temperature coefficient of magnetization for both isotropic and anisotropic barium-ferrite magnets is about $-0{\cdot}2\%$ per deg C, about ten times that of alloy magnets, owing to the ferrimagnetic nature of the material and to a Curie point of about 450° C.

The principal applications of barium-ferrite magnets have so far been for television focusing, cycle dynamos and some holding applications. Although applications development is increasing, there appear to be distinct limitations due to the difficult thermal properties. The material has good electrical insulating properties, unusual in a permanent magnet.

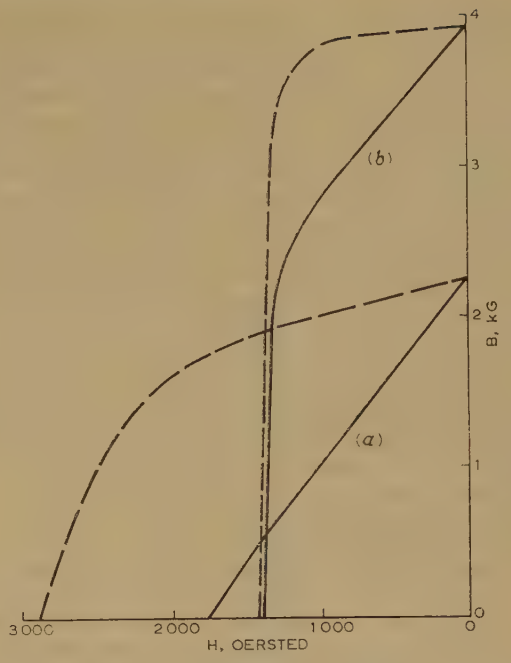


Fig. 2.—Barium-ferrite magnets.
—— B/H curves.
---- B_i/H curves.
(*a*) Random grain, isotropic, $(BH)_{max} = 1{\cdot}04$ MG-oersteds.
(*b*) Aligned grain, anisotropic, $(BH)_{max} = 2{\cdot}93$ MG-oersteds.

Although the major part of the ceramic magnet development is associated with barium ferrite, very similar properties can be obtained from the similar ferrites based on lead and strontium, but the higher cost of these has restricted development. There are patents covering the addition of small quantities of a number of other elements to barium ferrite. Some of the additions may facilitate manufacture, but there is no evidence of benefit to the magnetic properties attainable.

(6) MISCELLANEOUS SPECIAL MATERIALS

The materials already reviewed are used for the great majority of magnet applications, but there remain a number of materials with either limited specialized uses or with interesting future possibilities, as in Table 5. The earlier review[1] gave some details

Table 5

MISCELLANEOUS SPECIAL MAGNET MATERIALS

Designation	Composition	B_r	BH_{max}	H_c
	Weight %	G	MG-oersteds	oersteds
Cunife (U.S.)	60 Cu 20 Ni 20 Fe*	5 400	1·5	550
Cunico (U.S.)	50 Cu 21 Ni 29 Co	3 400	0·8	660
Vicalloy Vicalloy 1 (U.S.) Koerzit H (G)	52 Co 11 V 37 Fe	9 000	1·0	300
Vicalloy 2 (U.S.) Koerzit T (G)	52 Co 14 V 34 Fe*	11 000	2·8	400
P 6 (U.S.)	45 Co 4 V 6 Ni 45 Fe	14 000	0·4	45
Platinax	77 Pt 23 Co	6 500	9·0	4 000
Comalloy Remalloy (U.S.)	17 Mo 12 Co 71 Fe	10 500	1·1	230
Bismanol (U.S.)	79 Bi 21 Mn*	4 300	4·3	3 400
E.S.D. iron (U.S.)	50% Fe (by volume)*	8 800	3·3	715
E.S.D. iron-cobalt (U.S.)	42% Fe_2Co (by volume)*	9 050	5·0	1 025

(G), German; (U.S.), American; others British
* Anisotropic.

of the ductile materials, Cunife and Cunico, and also of Vicalloy, an iron alloy with about 12% vanadium and 52% cobalt which can be cold-worked, followed by a final tempering at 600° C, which both develops full magnetic properties and makes the alloy hard. These materials are in very limited production in some countries for specialized strip or wire magnets. There has been some development of a modified form of the cobalt-vanadium alloy, with replacement of part of the vanadium content by either nickel[24] or chromium,[25] thus obtaining a material of high remanence and moderate coercivity particularly suited for hysteresis motors. Technical development of platinum-cobalt alloys[26, 27] has led to a $(BH)_{max}$ value of about 9·0 MG-oersteds in conjunction with a coercivity of about 4000 oersteds, and this has found an application in battery-driven watch-motors.[28] There was a brief revival of interest in the cobalt-molybdenum-iron alloy known as Comalloy or Remalloy as a means of economizing in cobalt consumption at the time of the Korean war, but this soon flagged.

One of the new materials of great technical interest, but limited application due to cost, is manganese-bismuth. The compound (MnBi) has a hexagonal structure with a high uni-axial crystal anisotropy. The high coercivity of this material when in the form of small single-crystal particles and the possibility of useful permanent-magnet structures from a compact of such particles with aligned crystal axes were discovered by Guillaud.[29, 30] There were practical difficulties in the preparation and extraction of single-crystal particles of correct size and in their subsequent alignment and compaction; a substantial step forward was achieved in studies by the United States Naval Ordnance Laboratory,[31] with a realization of $(BH)_{max}$ of 4·3 MG-oersteds in conjunction with a remanence of 4300 G and a coercivity of 3400 oersteds. Subsequently, other claims[32] have been made for $(BH)_{max}$ values up to 7·3 MG-oersteds. The possible uses of the material are limited by the high cost of bismuth and by the same kind of temperature variation of the magnetic properties, with consequent liability to magnetization changes, as is found for barium ferrite. In the United States, some practical use has been made of the material in magnet systems for travelling-wave tubes.

It has become clear in recent years that permanent-magnet materials, however produced, approximate to assemblies of single-domain particles in which a relatively high field is required to change the magnetization axis of the particle owing to its inherent anisotropy. This anisotropy may arise from crystal form, as in barium-ferrite or manganese-bismuth, or from shape, as in the nickel-aluminium-cobalt-iron alloys. It has also been well demonstrated that an alignment of the particle axes gives considerable better permanent-magnet properties. As a first consequence of these theoretical developments, there arose the micro-powder iron and iron-cobalt magnets developed in France,[1] but these were of heterogeneous shape with only a small possibility of producing a favourable alignment, and, although of great technical interest, manufacture has now ceased. The full theoretical possibilities of shaped particles were revealed by Stoner and Wohlfarth,[33] and excellently analysed and compared with known materials in a United States Government report.[34] Briefly, elongated particles of iron of critical size for single-domain behaviour have a theoretical intrinsic coercivity, when isolated or in dilute dispersion, of 10000 oersteds; induction is proportional and coercivity approximately inversely proportional to packing factor, so that an aligned assembly of such particles, with 50% of the volume occupied by iron, should have properties of the order of: remanence, 10000 G; $(BH)_{max}$, over 20 MG-oersteds; and coercivity, 4500 oersteds. Iron-cobalt particles, with higher saturation magnetization, should give even higher values. In 1955 the achievement of such elongated-particle assemblies was reported,[35] with particles of a mean diameter of 150 Å, an elongation ratio of 4·5, giving a dilute intrinsic coercivity of 2050 oersteds, and, from a 50% compact, a $(BH)_{max}$ of 3·3 MG-oersteds. These particles are obtained by carefully controlled electrolysis of iron into mercury, and subsequent heating and extraction.[36] Later work has given better values from cobalt-iron particles and has shown a close comparison with the properties of nickel-aluminium-cobalt-iron alloys,[37] although there is now reason to doubt whether the predicted theoretical coercivities can be achieved.[38, 39] To what extent this method of permanent-magnet synthesis can economically compete with older methods is not yet clear.

As a by-product of the investigation of elongated particles, the possibility of a completely novel means of improving permanent-magnet properties has been discovered, namely a displacement of the hysteresis loop so that coercivities are unequal in the two directions of magnetization of a single axis. Meiklejohn and Bean[40] have found this effect in cobalt particles with an oxide layer by cooling in a magnetic field to below the Néel temperature (300° K) of the antiferromagnetic coating; they ascribe the effect to spin coupling between cobalt atoms in the metal and cobalt ions in the oxide, and suggest the name 'exchange anisotropy'. At present this effect can be found only at sub-zero temperatures, but knowledge of antiferromagnetic compounds and alloys is expanding rapidly, and one can foresee the possibility of greatly improved permanent magnets subject to a certain unique combination of properties. In the nickel-aluminium-cobalt-iron alloys, a high-temperature solid solution nucleates on cooling to give elongated magnetic particles in a substantially non-magnetic matrix, and, since the Curie temperature of the particle material is higher than the nucleation temperature, the particle orientation can be controlled by cooling in a magnetic field. If a similar system could be found in which the matrix material became antiferromagnetic at some temperature between the Curie temperature of the nucleated particles and room temperature, permanent magnets consisting of a domain assembly with only one easy direction of magnetization would result. The properties and stability of such magnets should considerably exceed those of the presently used magnets with a uni-axial anisotropy (two easy magnetization directions).

(7) BONDED MAGNETS

Various types of powder magnet have already been mentioned, but there is another class, based on completely different principles, which has found little favour in this country, although in regular production in Germany and elsewhere. Both nickel-aluminium and barium-ferrite magnet alloys are very brittle and are difficult to produce to precise dimensions. It is relatively easy to crush either material to a fine powder, yet with particle size considerably greater than that associated with single-domain behaviour, so that the magnetic macro-properties are preserved in the particle. Such powders can be mixed or coated with a plastic and moulded by compression or injection methods to fairly precise sizes, in which a little over half the volume is occupied by magnet powder; the compact has a remanence of about half, a $(BH)_{max}$ of about a third, and a coercivity much the same as that of the solid isotropic magnet material which has been incorporated. The ratio of properties is much less for crushed and bonded anisotropic material, so that no advantage is found in its use, and attempts to use field-aligning methods to increase properties have had little success. Hennig[41] has reviewed the possibilities of the process, and typical properties are as in Table 6. There is no reason why the bond in such materials should not be of a rubber-like material, and flexible permanent magnets made in this way are being produced.

Table 6

RESIN-BONDED MAGNET COMPACTS

Designations	Magnetic constituent	B_r	$(BH)_{max}$	H_c
		G	MG-oersteds	oersteds
Oerstilit (G) Prac (G) Tromalit (G) Agglomere (F)	Alni Alnico	3 000 3 500	0·5 0·7	500 600
Caslox III Oxilit (G) Prox (G) Plastoferrite (F)	$BaO\,6Fe_2O_3$	1 500	0·45	700

(F), French; (G), German.

(8) CONCLUSIONS

An attempt has been made to survey the main features of each class of permanent-magnet material at present in general use and also to mention the more interesting of the materials which have been under recent development, even though their future is still uncertain. In terms of present consumption, the anisotropic alloys produced mainly by casting, but also by sintering, and subjected to heat treatment under a magnetic field cover most permanent-magnet requirements. The more recently developed barium-ferrite magnets are finding increasing applications, have the benefit of a low raw-material cost, but have disadvantages in temperature stability. The developments in fine-particle magnets based on the theoretical conception of single-domain particles with anisotropy arising from shape are of the greatest technical interest, but still of uncertain economic value.

As regards applications, the electromagnetic applications in which a permanent magnet provides the field for a current-field-force interaction still predominate and expand, although the greater energy and coercivity of present materials is leading to even greater expansion of permanent-magnet uses for holding and fixing devices of all kinds, from simple domestic applications to motion transmitters in nuclear power stations. It may be noted that the magnetic characteristics, the mechanical properties and the manufacturing techniques necessitate a very simple shape for modern permanent magnets, so that the use of pole-pieces is almost universal. The increase in available energy has tended to reduce the size and weight of permanent magnets for any specific application, although there has simultaneously been an increase in the maximum size of permanent-magnet assemblies to cover such diverse uses as rotors for generators of several hundred kilovolt-amperes capacity, machine-tool chucks, automatic train control and nuclear magnetic-resonance equipment. There has also been a marked expansion in the environment in which permanent magnets are expected to operate with reasonable stability, notably in temperatures from below −100°C to about 600°C and when subject to intense neutron bombardment.

Present production practice in the permanent-magnet industry makes available a wide range of satisfactory materials, but there is little doubt that the theoretical and experimental work in domain magnetism now being carried out in many different centres will give even better future materials.

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DISCUSSION ON 'THE APPLICATION OF TRANSISTORS TO PHASE-COMPARISON CARRIER PROTECTION'*

Mr. J. Rushton (*communicated*): One of the most difficult aspects of the design of any protective scheme is the preparation of a technical performance specification. Phase-comparison systems are no exception, and the problem stated simply is to determine the loci of possible phase angles under internal fault and healthy system conditions and to provide a relay operating characteristic which will discriminate between these two conditions.

Internal fault conditions have been examined in part by the authors in justification of their choice of phase-comparison quantities; it may well be, however, that more complex faults might modify the author's conclusions, particularly with regard to phase-angle considerations.

The locus of phase angle under healthy system conditions has been examined by Donaldson,† and Fig. A shows the typical application for a 275 kV line. The diagram also shows the addition of carrier transit time to give the overall phase displacement between the comparison currents.

The diagram indicates two fundamental design requirements of the protective scheme, first that the stability angle shall be adjustable, and second that the scheme shall be provided with a definite current setting, or more precisely that the high-set relay setting shall exceed the low-set by the correct margin. Ideally the low setting should be as low as possible consistent with non-continuous carrier signal.

The 30° angle quoted in Section 1.1 was arrived at following a consideration of 132 kV Grid lines under internal and external fault conditions using a summation current-transformer output and must necessarily be increased for the longer higher-voltage lines unless some form of compensation is included. Indeed, without such compensation it is possible in such cases that the application of phase-comparison principles using a single-phase output for comparison purposes will prove abortive.

The authors include a 'rate of change' starting feature to cover the 3-phase fault condition in line with common practice. This suffers from the obvious disadvantage that a low fault infeed may differ insufficiently from the pre-fault load flow to produce operation, and presumably the authors' intertrip feature is intended to cover this condition, although it is by no means

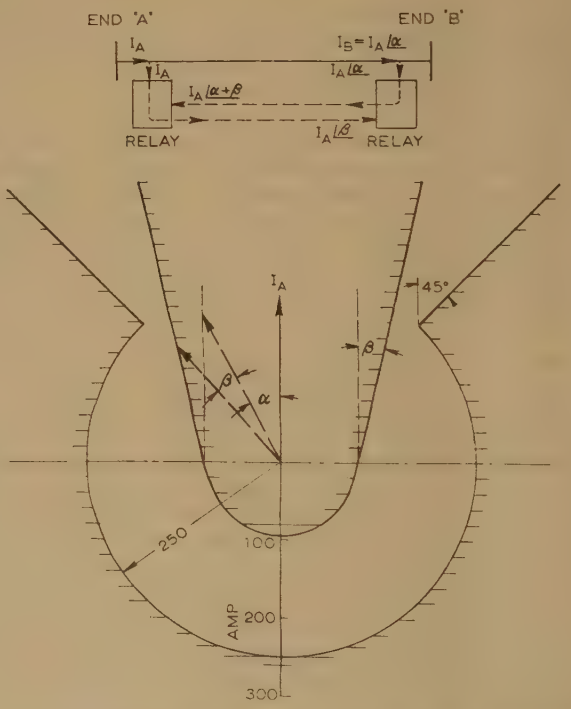


Fig. A.—Application diagram for phase-comparison protection of a 100-mile 275 kV line.

The relay characteristic also is shown (current setting, 250 amp; phase-angle setting, 45°).

— — — Envelope of $I_A \angle \alpha$.
——— Overall phase-comparison envelope $I_A \angle \alpha + \beta$.

* ADAMSON, C., and TALKHAN, E. A.: Paper No. 2793 M, February, 1959 (see 106 A, p. 51).

† DONALDSON, G. W.: 'Application of Phase-Comparison Principles to Power-Swing Conditions on Long High-Voltage Transmission Lines', *Proceedings I.E.E.*, paper No. 1090 S, February, 1951 (98, Part II, p. 47).

certain that the fault condition would not affect carrier reception. Also, the variable sensitivity of the 'rate of change' circuit is unsuitable for operating the high-set feature. A more straightforward solution is to use a single-phase modified impedance starting relay to cover the 3-phase fault condition, since all transmission lines are provided with at least one voltage transformer for synchronizing purposes.

Mr. C. Adamson and **Dr. E. A. Talkhan** (*in reply*): We are grateful to Mr. Rushton for raising the points which are of greatest interest in the application of carrier to power-system protection. The issue of stability angle is clearly of increasing importance as the voltage level of feeders is raised, and for this reason the angle has been made adjustable in the basic design of the protection system; reference is made to this adjustment in the paper, and it is incorporated in the integrating circuit of the phase comparator (Fig. 6).

So far as the application of this type of protective system is concerned, the issue is the extent to which the total tripping angle [Fig. 17(*a*)] can be sacrificed. If the application engineer cannot tolerate a reduction of total tripping angle below a certain figure, say 270°, then either compensation must be invoked or an alternative form of protection adopted. In our opinion, based on transient experiments carried out on our laboratory protective-gear test equipment, this latter eventuality is unlikely for the case of two terminal lines.

With regard to the additional incursion into the tripping zone, as indicated in Fig. A, such a situation is avoided in the system described in the paper by the function of the starting circuit; under symmetrical fault conditions, this is set for levels greater than the incursion of the swing characteristics of Fig. A, into the tripping zone of the relay.

Our paper entitled 'Selection of Relaying Quantities for Differential Feeder Protection' is shortly to be published by The Institution; this will go some way to meet Mr. Rushton's comments on the use of internal fault conditions to justify the choice of derived phase-comparison quantities used in the present paper. It must suffice for the time being to say that all single-shunt and series fault conditions have been considered, together with all combinations of positive, negative and zero phase-sequence quantities, and the special case of the summation transformer with primary-side ratios of $1 : m : n$. It is our opinion, arising from this work, that the choice of positive plus a weighted amount of negative phase-sequence current is the best solution. The analysis becomes very complicated and tedious, however, and in the later stages of this work a transformer-analogue network analyser was used. This analyser is also being used to pursue further the question of complex faults, and it is hoped that more information will be available before long.

With regard to the 'rate-of-change' starting feature, it can be seen from Fig. B, that the rate-of-increase signal is always superimposed on any pre-fault load flow and that, in consequence, operation takes place at the same current level on the power line irrespective of pre-fault load conditions. Thus, in Fig. B(*b*), although the amplitude of the starting pulse is low, its leading edge still crosses the pick-up level, which is all that is necessary to give correct operation.

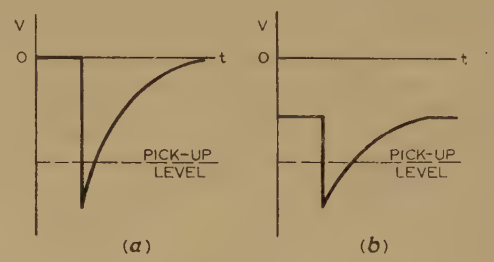


Fig. B

The use of a modified impedance starting relay for use in cases of balanced faults is a possibility. We do not consider that this is clearly a more straightforward solution, since, depending on the type of distance relay chosen, it may be susceptible to transient maloperation, and in any event may give false starting during power swings.

DISCUSSION ON 'INVESTIGATIONS OF POWER FOLLOW-CURRENT PHENOMENA USING A SYNTHETIC POWER SOURCE'* AND 'THE IMPULSE INITIATION OF ARC DISCHARGES'†

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 8TH DECEMBER, 1958

Dr. D. Whittaker: For the 10 cm-gap positive impulse Paper No. 2707 gives values for i_0 between -5 and -12 amp when using the lower values of Z. Under these conditions it would seem that the formula given in the Appendix for calculating t_1 should be altered to $i_{t1} - i_0 \simeq v_0 t_1/L$, which may increase the required value of t_1 by a factor of ten.

The current $i_0 \simeq -v_{gt}t_0/L$, where $v_{gt} \simeq v_{IG0} - i_{IGt}R_F$ during the time t_0. As Z decreases the authors explain the increase of i_0 (Fig. 6, Paper No. 2707) by the major effect of L decreasing and another effect of t_0 increasing. Calculations show, however, that the fact of v_{gt} decreasing has a bigger effect than t_0 increasing, and so i_0 increases less rapidly than Z decreases, which agrees with the experimental results.

Because di_t/dt is proportional to $1/Z$ $(0<t<t_1)$ and i_0 increases less rapidly than Z decreases, the large negative values of i_0 alone can never compel critical v_0 to rise with reduction of Z. This is contrary to the statement at the end of Section 6 (Paper No. 2707), which therefore cannot explain the increase of critical v_0 with decreasing Z shown in Fig. 5. An explanation which is valid if the value of C_{IG} is less than about $0.01\,\mu$F (assuming $R_F = 5$ kilohm) is that a value of critical v_0 which would be expected to give a satisfactory value of i_{gt1} may be unable to

* ALSTON, L. L., and BRUCE, F. M.: Paper No. 2707 S, November, 1958 (see 106 A, p. 123).

† ALSTON, L. L.: Paper No. 2708 S, November, 1958 (see 106 A, p. 133).

maintain a sufficient value of i_{gt} ($= i_{IGt} + i_t$) at some time less than t_1. Because i_{IGt} falls exponentially while i_t rises only linearly from a negative value, i_{gt} may tend to become negative. Therefore critical v_0 must be greater than that determined solely by conditions at time t_1.

The current i_0 is evidently important in determining the success of arc initiation, especially for the lower values of Z when using the 10 cm gap. Because of the dependence of i_0 on t_0, could the scatter in the values of critical v_0 be caused by variations in the time lag associated with spark breakdown? It is most desirable to keep t_0 to a minimum, by over-volting the test gap, by irradiation and by keeping stray capacitance of the impulse circuit and test gap to a minimum.

Dr. H. Edels: I am pleased that the authors' results appear to substantiate reasonably my earlier criterion that arc initiation will occur if the impulse-generator discharge has a voltage, v_s, which is less than the power-source voltage, V, for a time long enough to allow the current from the power source to build up to an arc value. The critical condition, it is suggested, is when this time is just sufficient for the current to reach the glow-to-arc transition value. Consideration of the author's results led me to propose in the London discussion a modified criterion for positive-polarity follow. This criterion, and the authors' work also, indicate that high-voltage follow might be more suitably defined as 'glow follow' and, similarly, heavy-current follow as 'arc follow'. In this way the curves in Fig. 3 of Paper No. 2707 can be continued into the h.v. region. From Table 2 of this paper it would appear that for positive polarity the i_{gt1} values reflect true critical gap conditions. However, for negative polarity the i_{gt1} values must surely represent the currents in the power source at t_1, and do not therefore denote gap conditions.

Dr. L. L. Alston and **Professor F. M. Bruce** (*in reply*): In reply to Dr. Whittaker, the formula for calculating t_1 is given in the Appendix for the case of i_0 being negligible: this is stated in the line in which the formula is given. There is therefore no question of t_1 being increased by i_0. It is explained in Paper No. 2707 that it is both desirable and practicable to design synthetic circuits so that i_0 is negligible, and Dr. Whittaker's concluding paragraph supports this view.

With reference to Fig. 5 of Paper No. 2707, Dr. Whittaker discusses in detail the mechanism by which v_0 is increased when Z is reduced. He explains that, if i_t builds up from a negative value, i_{gt} may tend to become negative, so that a large v_0 is required for arc initiation. Now, the initial negative value from which i_t builds up is, in fact, i_0. If i_0 is relatively small, i_t becomes positive while i_{IGt} is still large, and there can be no question of i_{gt} becoming negative. If, however, i_0 is relatively large, i_t may remain negative for a relatively long time, during which i_{IGt} falls to a low value; in this case, v_0 may have to be increased in order to prevent i_{gt} from becoming negative. Dr. Whittaker's discussion therefore shows that the increase in v_0 is due to i_0 being large, which is what we said in Section 6. We agree that this appears to be contrary to Dr. Whittaker's earlier statement that large negative values of i_0 alone cannot compel the critical v_0 to rise.

Dr. Edels's comments are gratifying. We are aware of his work in this field, and we have discussed it in Paper No. 2708 (Section 4). The criterion to which he refers is, in fact, that which we have derived from eqn. (2) of that paper, and from which we have derived the more precise glow criterion. The criteria for high-current follow are different, and are given in Paper No. 2707.

It would be misleading to differentiate between the two mechanisms of follow current by the terms 'arc follow' and 'glow follow', because in both cases the establishment of follow current implies the initiation of an arc. The discharge does not necessarily degenerate into a glow when high-voltage follow current is initiated. Glow periods occur only under limiting conditions, and even then their duration is short compared with that for which the discharge has an arc characteristic.

Dr. Edels's comments on Table 2 are true and self-evident. The significance of 'critical' is defined in the Papers; it is critical for our experimental conditions, which include the gap and the circuit. We have shown, however, that on positive polarity the gap current corresponds to a critical gap condition.

DISCUSSION ON
'RECENT DEVELOPMENTS IN MEDIUM-VOLTAGE H.B.C. FUSE LINKS'*
SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP, AT BIRMINGHAM, 12TH JANUARY, 1959

Mr. J. A. Robbins: The author's comments on the attempts made to achieve some uniformly acceptable standard for fuses for both the U.S.A. and Canada are extremely interesting, although it is never an easy task to persuade other countries to adopt our standards. We have recently had a similar experience with miniature circuit-breakers when trying to persuade the various Continental countries to agree upon a common minimum tripping-factor. While in this country we think in terms of a tripping factor of 1·3, corresponding to the author's fusing factor of 1·3, the Continental countries are quite adamant that they want a factor of about 1·8 to correspond to normal fuse performance. In other words, while we like to take advantage of the closer protection that these circuit-breakers can give, the Continental attitude is that nothing must interfere with their accustomed practice of loading a 10 amp circuit to 15 amp.

I am interested in the attempt to design fuses to give close protection without deterioration. This is quite a worry to starter manufacturers. Quite recently we have had several instances of coil failures caused by fuse deterioration and consequent low voltage on the coil.

A final point of interest is the author's comment that, in the United States in particular, it is felt that rapid operation under heavier fault conditions is desirable, in order to give better earth-leakage protection. This in some ways is rather a myth. For complete shock-risk protection at normal voltages, circuit isolation should occur in about 10 millisec. It would need exceptionally good earthing conditions for even a 30 amp ring-main fuse to clear in times of that order.

Mr. W. J. Elliott: Doubt is sometimes expressed about the possibility of obtaining in practice the high fault levels which have been calculated as the requirements of fuse specifications. In some recent tests on fault levels in a large factory we obtained figures varying between 18 and 2·5 kA. Comparison with calculated figures for the installation showed the greatest accuracy at the highest values, and nowhere was the error of calculation greater than 12%. There is little doubt that the breaking capacities specified in B.S. 88 are necessary, and even

* DEAN, R. H.: Paper No. 2419 U, October, 1957 (105 A, p. 263).

the high figure of 80 kA required by the C.S.A. can be met by a number of British manufacturers.

There is a limit to the use of very low fusing factors, unless the time lags of fuses such as those described in the paper are sufficient to allow the passage of starting current for a sufficiently long time. It is doubtful whether the 1 sec delay shown in the curves will be sufficient to pass this starting current without some derating of the fuses. B.S. 88 ratings go up to 1 200 amp, and with all fuses larger than the 600 amp rating, which is the maximum in the paper, it is likely to be difficult to meet the temperature-rise requirements at very low fusing factors unless physical sizes are increased. Since this would increase the size of the switchgear, it would be an unpopular decision.

Since one would not expect an accuracy greater than ±5% in fusing current for a given time, especially in the time-lag zone, it would appear that the author has been particularly fortunate in his choice of a fuse which could be run continuously at 95% of its forecast minimum fusing current. Is it not likely that the fuses have, in fact, a higher fusing factor than is aimed at in the design?

Mr. V. D. Long: Will the author compare the fuse-link ratings required with dual-element fuse-links and silver wire fuse-links, when used to protect motors with direct-on-line starting? What effect would these fuse ratings have on cable size when complying with The Institution's Wiring Regulations in connection with fuse rating to cable rating?

Mr. A. J. Mare: The fuse described has no external indicator and I do not see any mention of it in the paper. Is it purposely omitted from the design of h.b.c. fuses, or does the inclusion of an indicator upset the performance characteristics in any way?

Mr. F. N. Dalman: Does the care which the Americans take in choosing fuses with a small fusing factor mean that they use their material much more economically in cables than we do and therefore have less margin of capacity in the cables and more need to protect them?

I found difficulty in following the description of the dual-element strip where the author says that 'with two zones in series there are, on operation, two parallel circuits, each having four arcs in series', and shall be glad to have this clarified.

In connection with discrimination the author makes the point that if the pre-arcing constant of a larger unit is more than twice that of the smaller, discrimination will occur. From Table 2 I notice that, with fuses in the series of sizes given, the higher of any pair has a pre-arcing constant more than double that of the smaller, e.g. the 60 amp fuse appears to have a pre-arcing constant twice that of the 30 amp one, and so on. This suggests that discrimination is possible with 400 and 600 amp fuses in series. Will the author confirm this, because it is a much smaller ratio of sizes for obtaining the discrimination than I have previously seen?

Mr. T. D. G. Wintle: Consider the use of fuses with motor control gear; the starter itself must be capable, by specification, of breaking eight times the full-load motor current. Consequently, there is no need for close fuse protection, provided that the overload unit will carry out its duty and is of a sufficiently robust construction to withstand overload currents up to the minimum blowing current of a fuse.

During a recent visit to the United States I was told by a large fuse manufacturer that enormous numbers of American 'pennies' were collected from consumers' fuse units, and I suggest that part of the great popularity which the miniature circuit-breaker has achieved in America has been based on the view of the supply authorities that it is better to have a unit with which the consumer cannot tamper. I also found that increasing use is being made in North America of circuit-breakers including h.b.c. fuses—a very useful piece of equipment, because one has all the advantages of easy and correct restoration of the circuit up to fault levels of, say, 10 kA and the circuit-breaker itself is protected by the fuses on the few occasions when really heavy short-circuit currents have to be broken. The large number of rewirable fuses at present used quite successfully in this country show that fault levels of even 1 kA are unusual, and we should not deny ourselves the advantage of devices which have been used both in the United States and in Europe for many years.

The paper described a heat run of 43 hours. Is this a sufficient time to give a proper indication of deterioration? We have had criticism that 1 000 hours is insufficient for the small fuses used in 13 amp plugs, and I would therefore think that 43 hours is a very short period unless there is some statistical reason; if there is, I should be glad to have further information.

Mr. R. A. West: Many years ago I had some discussions with one of the author's colleagues on the question of h.b.c. fuse

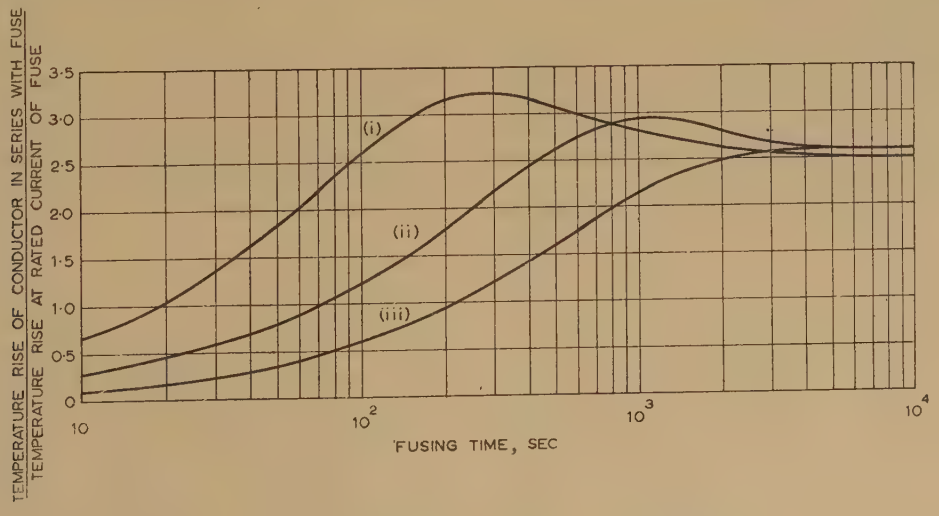


Fig. E.—Variation of heating effect with fusing time.

(i) 18 s.w.g. wire and 25 amp fuse.
(ii) 7 s.w.g. wire and 200 amp fuse.
(iii) 0·4 in diameter rod and 200 amp fuse.

protection, and it was claimed that the thermal memory of their fuse would enable it to protect a fairly large motor—say 75–100 h.p.—for starting a sugar centrifuge. It would be taking approximately its stalled current for 30–60 sec and then there would be a rapid fall off in current. How close is it possible to match the time-constant of the motor to that of the fuse? The apparatus to be started may have a high-inertia load, and it may be half-started and then stopped several times in succession.

Mr. S. Taylor: In Section 6 the author states that the energy-limitation ratio has a bearing on the calculation of cable heating and energy released at the fault. It is perhaps not generally appreciated that the most severe heating condition will not necessarily be produced by the energy which the fuse permits to pass when operating on maximum fault current.

The heating of conductor in series with a fuse is, of course, a function of $(1 - \varepsilon^{-t/\tau})$, where τ is the heating time-constant of the conductor and t is the fusing time of the associated fuse. When the values taken from a fusing-time characteristic are applied to this expression and plotted to show the variation of heating effect with fusing time, the result is as shown in Fig. E for three typical cases. It will be seen that there is an optimum fusing time which produces the maximum heating effect and in most cases this will be found to occur at the minimum fusing current.

Mr. R. H. Dean (*in reply*): This discussion follows lines similar to other centres, the main interest shown being in the low fusing factor of these dual-element fuses coupled with the capacity to pass, without deterioration, overloads of the magnitude of a direct-started motor, so that the current rating of the fuse may be of the same order as the full-load current of the motor.

Mr. Robbins points out that on the Continent they seem to have given up hope of obtaining protection either in small circuit-breakers or fuses on faults between 1·0 and about 1·8 times full-load current. In North America they insist on the gap being closed to 1·3 and obtain this economically. A fuse cannot provide shock-risk protection, but a low-fusing-factor fuse on a high-resistance fault will blow where a high-fusing-factor fuse will not operate and thus provide better earth-leakage protection.

I cannot agree with Mr. Elliott that fuses in this country should have breaking capacities in excess of the present maximum requirement of 46 kA. The North American requirement of 80 kA is for 600-volt fuses. Our voltage of 440 volts reduces the magnitude of potential fault. Up to a continuous fuse rating of 1·2 kA, cooling to fulfil temperature-rise requirement is not a serious difficulty; ratings of 2–6 kA would require artificial means of cooling. The minimum fusing current is defined in Clause 18 of B.S. 88: 1952, which permits a theoretical variation of 10%. We find that these fuses operate satisfactorily on 95% of the assessed minimum fusing current, as the tests to prove non-deterioration show. Variations in individual fuses, when subjected to these small overloads, do not seem to affect the current at which the fuse will operate so much as the time it takes.

Mr. Long asks for a comparison of silver-wire and dual-element fuses when used for cables controlling direct-started motors. This is given in Table A,* in which the dual-element figures are based on a starting peak of less than seven times the full load current of the motor for 2–3 sec—which approximates to five times for 10 sec. Rule 316 of the Wiring Regulations relates the current rating of the fuse to that of the cable. The effect of a fuse with a low minimum fusing factor can be dramatic, as shown in Table B.†

The provision of indicators to show a blow is raised by Mr. Mare. They are never used in North America, but in this country there are periods when they are fashionable, as at present. My opinion is that they quite often misfire, and unless such a device can be made 100% certain, it can be a source of confusion and danger. They also add to the cost of a fuse more than most people realize. Modern indicators do not, however, affect the performance.

Replying to Mr. Dalman, I do not think that the use of a small fusing factor affects the size of cables used in North America. Regulations vary, but, in general, the copper area seems to be much the same in both countries. Discrimination between, say, a 400 and a 600 amp fuse link is obtained, and an even closer ratio can be used if the available fault current is small. This is rarely required, however, and the rule of 2·1 between ratings is generally used.

I would remind Mr. Wintle that the paper refers to fuses for general distribution; fuse links for use as back-up protection in control equipment and switchgear are a particular duty I have not attempted to cover. They require special characteristics different from the ordinary fuse. The heat run to prove non-deterioration on minimum fusing current less 5% happened to stop at 43 hours. Any period of over 24 hours would be sufficient.

In reply to Mr. West, fuses are used as the sole means of motor protection only in special cases. All fuse links have to some extent a 'thermal memory', but the time-constants are much smaller than the apparatus they protect.

Mr. Taylor raises a very pertinent point when he shows that the most serious heating condition for a cable is not necessarily on maximum fault current, and his Fig. E. indicates this to be on currents associated with minimum fusing currents. The fusing factor of the fuse links used are not given, but I suspect that it will not be to Class P B.S. 88: 1959. The temperature rises shown are unlikely to be caused by a fuse blowing on 25% overload. These curves bring out a feature I have tried to stress in my paper, namely the wisdom of providing a fuse link with the capacity to blow on 25% overload after a suitable time. This is insisted on in North America.

* See 105 A, p. 276.

† See 105 A, p. 277.

DISCUSSION ON

'ELECTRICAL FLOOR WARMING'*

Before the North-Western Utilization Group *at Manchester 8th October, the* Southern Centre *at* Hove *16th October, the* Western Centre *at* Bristol *11th November, the* South-West Scotland Sub-Centre *at* Glasgow *4th December, the* Mersey and North Wales Centre *at* Chester *16th December*, 1957, *the* South Midland Centre *at* Birmingham *31st March, and the* North Staffordshire Sub-Centre *at* Stoke-on-Trent *21st November*, 1958.

Mr. G. V. Sadler (*at Manchester*): Since I spoke in the London discussion about the floor-warming scheme recently installed in a bay at our factory, I shall only add a few words about the floor construction, which may interest those contemplating similar schemes.

The whole floor had to be completely homogeneous, in order to withstand hard use and heavy loads. The heating tubes were therefore laid originally on a series of triangular concrete plinths, set up on the hard core before any concreting was commenced. They were set at the correct height to the finished floor. When the tubes were laid in a particular section, concrete was poured all round them, and finished complete to the working height. It was considered that, if the heating pipes were laid on an already hardened concrete base and a further 2½ in depth of concrete screed were laid on this, there would be a risk of cracking in use. So far, the construction adopted has proved satisfactory, but care was necessary to prevent any concrete entering the heating pipes at the joints.

The control gear for the whole scheme consists of four contactors suitably controlled by thermostats, and the load of 510 kW is divided into four approximately equal sections.

The paper mentions the use of a thermo-time regulator, but in our experience this has not proved sufficiently accurate to ensure that the load is completely off peak, and a further standard clockwork time switch has been inserted to ensure that off-peak hours are strictly adhered to.

With regard to domestic heating, I do not agree with the authors that the upper rooms of a house are sufficiently warmed by ground-floor heating, and I should be interested to know what arrangements have been developed for heating the normal timber floors of upstairs rooms.

I notice that recently an electrically-heated carpet underfelt has been introduced, but this would seem to have potential dangers to children, as against the more permanent built-in heating system in the floor itself.

I was interested to note the tariffs offered by the South of Scotland Electricity Board for off-peak domestic heating. The present comparable tariff in this area is 0·875d. per kWh for off-peak heating, as against 1d. per kWh for 24-hour heating. In addition, £2 per annum is charged for the hire of a time switch. I submit that this differential is not sufficient to encourage potential users to have off-peak floor-warming systems, and that a figure more nearly approaching 0·75d. per kWh is needed as an incentive to develop this load.

Mr. R. J. B. Hore (*at Manchester*): From the installation contractor's point of view, the solidly-embedded type of floor-warming panel has the advantage of simplicity and speed of laying. Since the element and its protection are combined in one unit, it is unnecessary for the electrician to make two visits to the site to carry out the job, and little storage space is required on site. It is also considerably easier to provide protection against corrosion for this type of system. The criticism usually levelled at the embedded installation is the difficulty and expense of repairing faults. This has not, in practice, been found to be a disadvantage; as the authors suggest, modern apparatus is capable of very accurate fault location, and the insertion of joints in the cable causes little disturbance to the floor structure. The selection of a solidly-embedded system has the merit of reducing capital costs, particularly those attributable to labour, and therefore it compares even more favourably with solid-fuel and other forms of heating.

Mr. F. A. Pullinger (*at Manchester*): The authors' contention that water-heated floor warming has not been much developed in this country is hardly correct. There are thousands of such installations and much research has been done, notably at the Building Research Station and the National College of Heating and Ventilating. The characteristics of floor heating are therefore well known.

There is no inherent difference between heating the floor with electricity or water in relation to comfort or heat input. Although it is true that lower *air* temperatures are possible with radiant systems (see Section 3.1), fuel consumption is not proportional to air temperature. Danter* shows that the required heat input to a room for the same equivalent temperature may be 5% less with floor heating (whether by water or electricity) at full load, but this improvement diminishes at partial load. There are also additional direct losses from the floor which may be as much as 15–20% of the total heat input to the room and can be significant in single-storey buildings. This is confirmed by Dick.†

Presumably the calculations in Table 2 refer to the school H in Table 1. As shown above, the heat input to the building will be at least as great with floor heating as with radiators. The savings due to the radiant source and the absence of second-order losses due to distribution are more than compensated by the direct floor loss. Normal calculations confirm that the input of electricity to the floor or the heat equivalent with fully-automatic clock-controlled oil firing with radiators would be about 1·29 GW per annum, no labour being required with either system. Automatic coal-fired stokers would need more heat, say 1·6 GW, owing to the need to kindle at night, and they would also require labour. Total capital costs of £22 000 would be amply sufficient for coal- or oil-fired radiator systems. Recalculating capital charges on this basis and assessing the fuel cost of oil at £1 800 would give the annual total heating cost as £4 170 against the electric floor-warming figure of £5 930.

Mr. J. B. Atherton (*at Manchester*): My criticism is not of the paper but of the employment of electricity for space heating unless (i) the energy is superfluous to other demands, and (ii) alternative more efficient, and less costly, methods are lacking.

Electricity generation is governed by coal supplies and plant capacity. Coal output has declined over the past 40 years (280 million tons in 1913 to 204 million tons of inferior quality

* Moule, J. W., and Stevenson, W. M.: Paper No. 2330 U, February, 1957 (see 104 A, p. 424).

* Danter, E.: 'Some Design Considerations of Floor Heating', *Journal of the Institution of Heating and Ventilating Engineers*, 1957, 25, p. 53.

† Dick, J. B.: 'Experimental and Field Studies of School Heating', *Journal of the Institution of Heating and Ventilating Engineers*, 1955, 23, p. 88.

in 1950). The National Coal Board is to raise this to 240 million tons per annum by 1965.

The Central Electricity Generating Board, for its part, will spend £300 million on atomic power stations, and is now heavily committed on new orthodox stations to make good the deficiencies of past years; this new plant will increase coal consumption to over 60 million tons per annum by 1965. A White Paper published in February, 1955, quoted a nuclear contribution of 2 GW (saving 6 million tons of coal) by 1965, but a total coal deficit of some 50 million tons is visualized. Failure to cope with the load is nothing new, if we recall the cuts and chaos of the years 1945–47. The electricity deficit in 1951 was quoted at 2·5 GW and increasing at the rate of 8% per annum. During 1946 the home market was flooded with 2 388 000 electric fires, which coincided with load-shedding. Although apparently not the concern of the supply industry, it was very much their concern to energize the fires. A widespread campaign of floor warming might prove equally irresponsible.

This country lags in world markets, and more power per man is required (the United States has three times ours) for a longer time. Round-the-clock working may come, and off-peak periods may vanish. If given only a limited amount of electricity for a factory, should it be used for power, heat, process or lighting? In the home, would you rather see, or have a warm floor, on a dark morning? The issue may be as simple as that.

Mr. W. N. Shires (*at Manchester*): I have recently been asked to prepare a scheme for heating a large garage which will require a load of 198 kW. It is planned to erect the building on a concrete raft, which will form the structural floor and protrude beyond the outside walls at ground level. I understand that end losses are considerable and should be minimized by the introduction of thermal insulation. In the circumstances, how would the authors include thermal insulation?

Mr. H. Coase (*at Manchester*): The use of off-peak electricity for heating is a logical development in power-station economy, but if it is to be attractive to the consumer, running costs must be truly comparable with those of other fuels for equal comfort. Electric cables in solid floor slabs are a wrong application. Thermal-storage systems with water as the storage medium are much preferable. The large storage vessels of pre-war and early post-war schemes need not be envisaged. The mid-day charge, the development of intermittent heating where the period of heating boost is in the off-peak charging period, and artificial pressurizing methods utilizing higher storage temperatures, all lead to smaller storage vessels.

Intermittent heating has been shown by Dick, Harrison and others to make for considerable fuel economy, and systems designed for intermittent heating should have low thermal capacities ensuring quick heating and short boost periods with rapid response to automatic controls. Embedded floor panels have the longest time lag of any system, and, as such, they are not suitable for intermittent use.

Heating engineers' experience suggests that equivalent temperatures of 65° F cannot be met with floor temperatures of 73° F. I do not understand how the heat is stored if 73° F is the maximum floor temperature. Since this temperature will be required later in the day to offset room heat losses under maximum conditions, the floor-surface temperature will have to be considerably higher than 73° F at the start of the occupied period.

How do room thermostats work, since they can neither call for heat nor shut it off when the occupied period coincides with the forbidden consuming hours? How does the storage-control thermostat 'guess' in the middle of the night what the outside temperature is likely to be on the following afternoon?

Mr. P. S. Watson (*at Hove*): The authors suggest that the emission of heat from a covered floor is affected by the emissivity of the material used in the covering, but they then state that, in rooms with fitted carpets, there is no appreciable loss of heat emission from the floor. Perhaps they can enlarge and explain this point.

In Section 4 it is stated that, for floor-warmed buildings, thermal insulation is specially important. I think the authors will agree that this is quite incorrect and that, whilst good insulation is beneficial, it applies to all buildings.

Since they are using the recommendations of the Institution of Heating and Ventilating Engineers, I do not understand why the authors should suggest that the electrical loading must be sufficient to ensure that the energy input during off-peak periods meets the heat losses during 24 hours. In my experience this is unnecessary, since the enormous heat bank established on the ground floors is sufficient to maintain comfort conditions during cold spells with a maximum of only 12 hours' heat input at calculated hourly heat loss. I agree that the basic design temperature should be lower than the normally accepted 30° F. In the south-east of England I am using 25° F in each case.

I am puzzled by the authors' contention that the controlling regulator should be designed to provide a minimum of four hours' electricity input each night. In fact, this seems wasteful, for experience in the south-east of England has clearly demonstrated that, on some warm evenings following a cold spell, no electricity was required during the night, whilst comfort conditions during the following day were well maintained by the thermal-storage properties of the warmed floor.

I challenge the authors' comment that floor warming is obviously unsuitable for heating a hall which requires only one or two hours' warmth occasionally. A church is being erected in the south-east of England, and it is proposed to heat it regularly by an input at off-peak periods of two hours per day. At week-ends a thermo-time regulator will be switched in to take over in the normal way. I believe that church heating, in particular, needs special consideration. On a cold day the congregation arrive warmly clad to withstand the external elements. In the absence of cloakroom accommodation they are obliged to sit warmly clad during the period of the service. It is thus obviously undesirable to attempt to heat the building to anything like the temperature required in the office or home, and, in my opinion, a moderate degree of heat, strongly supported by a warmed floor to give foot comfort, is ideal.

A machine has been developed in this country to cut slots in existing concrete floors so that solidly-embedded floor-warming cables can be laid. A test installation by this means will shortly be carried out at Orpington. This will provide the solution for those who are concerned with installing floor warming in existing buildings already fitted with concrete floors.

Mr. G. R. Lomax (*at Hove*): Having lived in an electrically floor-warmed house for over two years, I would not willingly change to any other form of space heating.

Before the method can be extended on a wide scale to dwelling houses, architects, builders and potential users alike must be converted to the necessity for building houses without chimneys, which are not required for floor warming. The aim for thermal insulation should be an overall value for U of 0·15 or less.

There are advantages in dividing each heating grid into two equal circuits so that alternative standards of heating can be obtained by using either series or parallel connections. This can be accomplished without significant increase in cost. The lower rating designed to give a 10–15° F rise may be used where there is no cheap off-peak tariff and/or to provide a high degree of background warmth only. The higher rating designed for a 30–35° F rise may be used for 'whole house' heating with restricted hours of charging. Auxiliary small-capacity portable

radiant heaters fitted with individual thermostats would provide 'topping-up' heat where required.

Mr. D. F. Hunt (*at Hove*): In Section 4.2 it is stated that the electrical loading must be sufficient to permit the energy input during off-peak periods to meet the heat loss throughout 24 hours. With a 12-hour restricted supply one would expect a loading calculated in the conventional manner to be doubled. In fact, we know that there are factors which make it unnecessary to double the load in such a case, but surely the fact that the intake is restricted means that some increment should be added to the calculated load.

Will the authors explain how this increment is calculated and why, in Table 1, which gives details of 12 installations, in only two cases are the installed loadings higher than the standard conversion factor would give, and, in fact, in five cases the loadings are lower than would be so obtained.

In Section 4.3 it is stated that the consumption may be estimated by multiplying degree-days by hourly heat loss and dividing by 3412. If this formula is applied to Table 1 a degree-day figure of approximately 1500 is required to balance the equation. This is surely too low for Scotland.

Mr. C. Morris (*at Hove*): The authors state that the residual moisture in normal cement screeds sometimes gives rise to considerable trouble, and often causes the finished floor covering to lift from the screed.

These difficulties can be obviated by use of a synthetic anhydrite screed, which is laid very much drier than cement, and, even under the most adverse weather conditions, completely dries out within ten days.

When a screed dries the moisture content is reduced to a point which is dependent upon the humidity and the temperature of the air. Thus a certain amount of moisture remains in the screed, although it gives off no more moisture and is 'dry' from the point of view of coverings. This residual moisture escapes from the screed when a drier and warmer air occurs, as is the case when there is floor heating and the screed layer is warmed.

The residual moisture of synthetic anhydrite mortar with 60–70% relative humidity and an air temperature of about 64–68° F is generally below 0·6% weight; that of a cement mortar, under similar conditions, is from 2 to 3% weight. If the floor-warming system warms the screed, the residual moisture is gradually driven off. However, this is no longer possible after the screed surface has been covered with a dense floor covering. Under these circumstances the adhesive material used is liable to be destroyed by the moisture, which cannot escape. Blisters can occur and the floor covering becomes unstuck. The greater the residual moisture in the screed, the more danger there would be of this happening. With a synthetic anhydrite screed the amount is low and there is little danger, while with a cement screed the danger is considerably greater.

Mr. W. M. Hime (*at Hove*): What are the authors' views on withdrawable and embedded systems, and under what circumstances do they recommend either system? With the monolithic type of floor used at Motherwell, is there much difference in the laying time for this type of screed, and also, when a very dry mix is employed, is there likely to be a reduction in the annual energy consumed in the first and second years? In other words, is the higher consumption in, say, the first two years due to moisture being driven off?

Mr. F. Richardson (*at Bristol*): The paper comes to the south-west at a time when public attention is focused on electricity generated from atomic power by the building of two such stations within a radius of 50 miles of Bristol. It is relatively well known that machine load factors in excess of 75% must be obtained to make the best economic use of this highly capitalized plant, and one of the ways of securing a bigger base load is to develop off-peak utilization.

Off-peak electrical floor warming is a comparatively cheap way of storing electrical energy, and the pioneering work of the authors and a few others is paving the way for the rapid expansion of this form of load development.

Although the climate in the south-west is somewhat milder than in Scotland, space heating in winter is essential. Off-peak electricity could be used much more extensively to heat the many new buildings under construction and contemplated, by means of floor warming which is cheaper to install than most orthodox systems. Over the last two to three years the South Western Electricity Board has taken positive steps to build off-peak loads, by offering attractive tariffs, and making these and the many other benefits of electric heating widely known throughout the Area. As a result, in 1956–57 we doubled the load connected during the previous year, which, although quite modest compared with the achievements in the south of Scotland, gives some indication of the scope of this form of heat. The main field at present is in industry and commerce, but domestic interest is growing rapidly.

The keenest critics of electrical floor warming are the supporters of oil and solid fuel, who usually base their criticism on a direct comparison of fuel costs. When the saving in capital charges, due to a cheaper electric heating system and the non-provision of chimneys and fuel storages, is taken into account, off-peak electric storage heating is often cheaper, even at present-day prices.

Table 2 of the paper gives a balance sheet for solid fuel and off-peak electricity supplies, which confirms the results of investigations made by this Area Board. A factor seldom taken into account by architects and heating engineers is the possible fuel price trends over the life of the buildings to be heated, which may be, say, 20–40 years. While this may be somewhat speculative, there can be little doubt that the advent of atomic power has brought us to the threshold of a new industrial revolution, which is bound to result in cheaper electricity in a world of rising prices.

In connection with a floor-heating installation in a new store at Plymouth, covering 15000 ft^2, we have been asked by the Factory Inspector to install an earthed-wire mesh above p.v.c. sheathed cables to reduce danger from electric shock. As similar requests have been made in Scotland and elsewhere, can the authors state whether this requirement is justified and effective in practice? Expanded metal is also used in the floor, above a particular withdrawable floor-warming system, and this is claimed to diffuse heat more evenly over the floor. Bearing in mind the low thermal capacity of the mesh, does this, in practice, diffuse the heat, and, if so, is it necessary to do so, having regard to the small temperature difference likely to exist between element centres?

The authors mention that floor-heating installations in buildings of substantial construction can be operated without a mid-day boost. Does this apply where acoustic insulation is used immediately under the screed to reduce sound transmission at intermediate floors in multi-storey buildings?

Mention has been made of edge insulation at ground floors of buildings; would the authors give details of the methods, if any, used at intermediate floors, in order to prevent heat transfer from the floor to the building fabric in multi-storey flats?

Much fundamental work has already been completed in developing electric storage floor heating, but some problems will bear further study. We are using the store previously mentioned as a research project, designed to give information on the operating characteristics of most of the floor-warming systems now known in this country, and also the economics of edge and

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complete underfloor insulation. It is hoped that the project will make a contribution to the growing knowledge of this technique.

Mr. F. P. Phillips (*at Bristol*): Do the authors feel that underfloor thermal insulation may usually be omitted? Would this also apply if the subsoil were very wet? When heating is switched on only at night, by how much does the total consumption in kilowatt-hours exceed what would be required by conventional electrical heating energized during the day?

How important is the earthed screen over a p.v.c.-insulated and buried conductor system?

Mr. G. Haynes (*at Bristol*): I am interested chiefly in the maximum demand created by floor-warming installations and in the design of low-voltage networks to meet this demand, if it is developed in domestic property. There is also the economic question of whether it pays to develop this load at off-peak rates.

With reference to the Kirkcaldy flats, a system load curve superimposed on Fig. 13 would have been of interest in order to show the effect of commencing the afternoon boost as early as 11.0 a.m. The low demand, 50% of installed load, or between 1·5 and 2 kW per flat, is, no doubt, accounted for by some consumers not able to afford the extra comfort of floor warming overnight and incidentally probably using their 2 kW fires during peak periods.

I do not think that water heating should have been restricted to the off-peak periods, as the heavy loading between 11.0 a.m. and 2.0 p.m. and from 7.0 to 9.0 p.m. is undoubtedly caused by the water heaters all cutting in together after the morning and afternoon washing-up. The demand during these two periods would have been reduced by 10 and 15 kW if water heating had been unrestricted.

The South of Scotland Board, being both a generating and distributing undertaking, is, no doubt, able to offer rates for off-peak loading more nearly matched to the cost of off-peak generation than other Boards. Is it possible to obtain special bulk-supply off-peak terms for this purpose?

Most of the installations referred to in the paper will require a substation for their supply, and the total installation would, no doubt, bring in sufficient revenue to cover capital expenditure.

The dwelling houses are somewhat different. With an off-peak demand of 7·6 kW per house for floor warming and with unrestricted water heating, the night after-diversity demand is likely to be in the region of 7 kW per house, and the afternoon peak, if floor warming is restricted until 2.0 p.m., would probably be about 8 kW. If heating commences at 11.0 a.m. the midday peak, with cooking, is likely to be 9 kW. An estate of 65 houses of this type could be supplied from a 500 kVA transformer, and the cost of supply is likely to be about £25 per house more than supplying an after-diversity demand of 3 kW per house. How is this cost to be recovered at the low differential that can be allowed between the bulk-supply tariff and the off-peak rate to the consumer?

It is noted that heating cables are sometimes laid in metal tubing with expanded metal across the tubes. Are there any adverse inductive effects from this system or are two cables laid in each conduit?

Mr. A. K. Podkolinski (*at Bristol*): The system used for heating the wooden floor in the gymnasium of St. Mungo's School could presumably be applied for converting existing domestic dwellings where the normal concrete screed could not be used. It would be interesting to know whether it was entirely satisfactory. The top-layer hardwood strip approximately 1 in thick acts as a fairly good heat insulator, and to achieve a surface temperature of 73° F, the heating element must reach a considerably higher temperature. Is any fire risk introduced? I would also like to know whether the warm mass of sand used as filler between the wooden supports attracts vermin.

Mr. W. F. W. Lewis (*at Bristol*): I want to draw attention to points in the paper which might be fastened upon by competitors in the heating field anxious to discredit electrical floor warming.

For example, the consumption of electricity in Table 2 is given as 1·29 GWh, and this is equated against a solid-fuel consumption of 500 tons. It can be shown that, taking average calorific values, in terms of heat input the efficiency of the solid fuel system is as low as 30%. This would certainly be open to dispute, and 50% might be taken as a more reasonable figure for system efficiency.

It would be of greater help in advancing the cause of electrical floor warming if a comparison with oil firing were given. It is likely that oil will be the main competitor in this field in the future, at least for new buildings. In general, the financial advantage of electrical floor warming compared with central heating from oil-fired plant is likely to be much more marginal.

Mr. R. D. Hoskin (*at Bristol*): The introduction of various methods of off-peak loading is necessary if load factors on generating plant are to be increased.

The criticism has been made that, as the thermal efficiencies of conventional power stations will not be very much greater than 28–30%, the utilization of the fuel by the introduction of floor warming, rather than more conventional methods, is not likely to be improved very greatly.

However, the utilization of fuel in thermal power stations is still very much better than the average domestic installation, and, allowing for this, the conversion of domestic heating from solid fuel to electric should still produce considerable overall savings in solid fuel, particularly of large coal, which is of most value to the coal industry commercially.

With increasing numbers of nuclear power stations coming into operation, base-load requirements will increase, and floor warming seems the ideal solution to the problem of finding an off-peak load.

In spite of present fuel surpluses, we are likely to be short of coal in the next decade by several million tons each year, and although part of this deficit will be made up by nuclear power generation, fuel will have to be imported to fill the gap resulting from a deficit in our indigenous fuel supplies.

The universal acceptance of improved methods of domestic heating could do much to close the gap, and greater support should be given to all proposals affecting our fuel economy. Electrical floor warming is only one way towards this end, but it is of added importance owing to its beneficial effect on the generating industry in respect of loading.

Representations should be made to all responsible bodies to encourage this type of heating, by reducing off-peak tariffs as much as possible and removing the ridiculous anomalies that demand the payment of purchase tax on off-peak storage electric heaters but not on floor-warming cable installations.

The paper demonstrates that we are no longer talking in abstract terms about space heating by floor warming, but that large-scale installations are economically worth while and are practical propositions. We can look forward to increasing interest in this type of heating in the immediate future, not only by local undertakings, but also by industrial users.

Mr. R. H. Cobbold (*at Bristol*): In industrial buildings, difficulty could arise in positioning machinery fixings to avoid cables. What recommendations would the authors make to ensure that the precise position of heating cables is known when it is necessary to cut the floor for fixing bolts? Difficulties might also arise if it were necessary to put down a foundation block, the need for which could not be anticipated when the original construction took place, or if it were necessary to construct a sump. Would any danger arise if volatile cleaning fluids had to be used on a heated floor?

In general, it would seem that the inflexibility of the under-floor system might involve serious restrictions on the change of use of a building, which, in turn, suggests that the useful life of the heating system should be considered to be relatively short.

For domestic purposes, simplicity of control is important, and the regulators described in the paper might be beyond the comprehension of many people. As reasonable running costs depend on careful control, the importance of its being readily understood and maintained is considerable.

The paper gives no figures for downward heat loss, which might be considerable, nor does it give any figures showing how much heat is stored in floors of various designs. This information would be of value in balancing requirements against calculated heat losses from the building.

Mr. R. Croft (*at Glasgow*): In the paper several floor temperatures are mentioned, and in the south of Scotland the authors design for a maximum floor temperature of 73° F. In Glasgow we have some schools with good thermal insulation and others are not so good. On the average they compare favourably with schools elsewhere, but with the large area of glazing and the two air changes required, I find it impossible to design for a maximum floor temperature as low as 73° F. Thus I prefer the more realistic maximum limit of 77° F, which the recent research of Chrenko establishes as a safe maximum for the avoidance of foot discomfort.

An interesting point in the paper is the mention of the maximum temperature drop at Sighthill Health Centre of 2·6° F while the supply was off. Can the authors state the period of discontinuation and the drop in floor temperature during that period?

In Table 1, for school E it is stated that the design was based on 20° F outside temperature, and it would appear that school D was based on 28° F. This gives average internal temperatures of 62° F for E and 55° F for D, corresponding to the specified classroom and corridor temperatures, respectively, these being almost the highest and lowest limits encountered in schools. I should have expected average values between these extremes. Can the authors explain this fact, and also that the loss per square foot seems low for a school, that is compared with what I have experienced.

It is stated that the heat loss continues for 24 hours a day, and so, at first sight, it would appear that, if electricity were supplied for only 16 hours a day, 50% should be added to the heat losses to get the installed load. For several practical reasons considered elsewhere, such a high addition is not usually necessary—20 or 30% usually suffices. From Table 1, again I note that the installed load in cols. 6 and 7 is only the heat loss of col. 5 converted to kilowatts without any addition.

With regard to floor insulation, I was pleased to note that the authors are doubtful of the economic value of overall insulation. I agree that there might be a case for edge insulation in a small building like a house, where the perimeter is large compared with the floor area, but I am not sure that it is worth while in larger buildings. The A.S.H.A.E. Guide gives the ground-floor heat loss as 0·81 B.Th.U./ft of exposed perimeter with no insulation and 0·55 B.Th.U./ft with the best edge insulation. This means that, in a classroom with an exposed perimeter of 24 ft, the loss is less than 100 watts, which is small compared with a normal classroom loss of 6–7 kW. Is it worth while troubling the architect and complicating the structure for this?

Mr. Ll. Phillips (*at Chester*): There are many occasions when the whole floor area of a room or building is not available for the installation of floor-warming cables. How do the authors calculate the floor-surface temperature which will obtain in specified conditions and thus ensure that a maximum temperature of 75° F is not exceeded?

Mr. W. A. Hatch (*at Chester*): I can confirm the comfort conditions of floor warming compared with conventional convection heating after several months' experience in a large new block of residential flats having living-room areas of 20 × 15 ft. The unpleasantness of cold feet and legs, and also inherent draughts, has been eliminated. However, it is most desirable to supplement floor warming in a living room by a 'booster' in the form of a 1 kW electric fire. This enables the basic room temperature to be kept to a lower figure and also provides a focal point of heat for added comfort with a quick response to any change in temperature requirements.

It is not always realized that floor warming should be regarded as a central-heating system and should be switched on at an appropriate date and left on for the season under thermostatic control, because there can be no quick response by switching when dealing with such a large slab of concrete.

In normally humid areas such as Lancashire, watch should be kept on valuable furniture, since warping and shrinkage have unfortunately been observed as a result of extended drying-out.

In the not-too-distant future, when nuclear power stations are making a considerable contribution to our total energy requirements, it is conceivable that, with off-peak tariffs, floor warming will be the cheapest form of heating in new buildings. A possible competitor might be district heating for large garden villages, with hot water provided by a reactor station sunk in the ground at some central distribution point.

Mr. J. H. Addenbrooke (*at Birmingham*): At a previous meeting of the Supply and Utilization Group of this Centre, a paper* was given on the operational experience at Calder Hall nuclear power station. While the technical aspects of the two papers are poles apart, I suggest that they are commercially and economically connected, and, as the authors have stressed, it is most important that we develop loads for these new power stations, particularly during the night hours. I sometimes think that all Sections of The Institution do not always appreciate this point.

I have had an opportunity of seeing the flats at Kirkcaldy and also at Glasgow, and I was impressed not so much with the technical aspect, because the authors have ensured that was correct and efficient, but with the opinions of the people living in the flats. I believe that the main industry of Kirkcaldy is linoleum, but there are also a number of mines near there, and miners are living in these flats. Miners are invariably in favour of coal heating, but we were able to ascertain that those living in the flats were impressed and satisfied with the conditions.

I would like to quote from the report of the Borough Engineer of Kirkcaldy:

> Perhaps the most outstanding happening in the year just finished is the tremendous interest created throughout the country in our experiments in all-electric houses, particularly in the matter of electric floor heating. Some 40 English housing authorities have sent deputations to Kirkcaldy to enquire into the efficiency and economics of the system and the reaction of the tenants. As a result of the work done in Kirkcaldy, a number of English cities, including London, Birmingham and Wolverhampton, proceeded with electrical floor warming.

It is pleasing to note that, of the three places mentioned, two are in the area of the South Midland Centre of The Institution.

The authors have mentioned commercial and industrial applications of electrical floor warming, such as in omnibus garages, and a further industrial application is the pre-drying of special bricks prior to firing. Have there been any problems due to the concrete cracking after installation?

Mr. R. A. Shilston (*at Birmingham*): Electrical floor warming is used primarily to take energy at night in order to generate

* STRETCH, K. L.: 'Operational Experience at Calder Hall', *Proceedings I.E.E.*, Paper No. 2594 S, April, 1958 (105 A, p. 475).

and store heat which is given off throughout the day. Fig. 6 shows that, for several days, the outside temperature was below the design figures. It has been suggested that satisfactory internal temperatures are obtained because of the large storage effect of heated ground, which can emit for limited but long periods more heat per day than has been generated by the energy used during the same period. When heating cables are embedded in a comparatively thin screed, such as in blocks of flats where acoustic insulation is provided below the screed, are prolonged cold spells likely to give rise to unsatisfactory air temperatures?

I would welcome information regarding the calculation of installed loads and electricity consumptions. The paper indicates the rational methods of calculation, but these do not correspond with the figures in Table 1. In most cases the hourly heat loss is almost exactly equivalent to the installed load and in only three cases is there more than a 10% margin. Where energy is supplied at off-peak rates for, say, 15 hours per day, the installed load should be 24/15 times the equivalent hourly heat loss. Can the authors confirm that off-peak supply is used for these installations, and if so, for what periods? If the rational method has not been used, can they indicate what alternative calculation is correct? There seems to be a similar discrepancy between estimated annual consumption in Table 1 and the results obtained from the formula in Section 4.3.

Mr. S. C. Dinenage (*at Birmingham*): The authors state in Section 3.2 that heat 'disappears downwards into the earth', and later, that 'downward heat loss can be minimized by . . . a layer of heat insulation material under the floor'. With a storage-heating installation on a dry site, heat that is conducted downwards into the soil remains stored there until temperature conditions enable it to be recovered and make a useful contribution to the heating requirements. Except on a damp site, the introduction of insulation other than at the perimeter may reduce the building's thermal inertia on which we rely.

In Section 5.1.1 screed thicknesses of 1½ or 2 in are mentioned. My experience has been that, for thermal storage, 2 in is the absolute minimum and 3 in is to be preferred. With the thinner screed, thermal resistance to upward heat flow is low, and a balance between input and output is reached too soon in the charging cycle. Increasing the screed thickness enables more heat to be stored both above and below the cables.

A problem arising in domestic premises where radiant heating is employed for 'topping-up' purposes is the difficulty of ensuring that a full charge is put into the floor when the radiant heating provides a substantial proportion of the total heating, holding off the thermostat controlling the floor warming until late in the permitted charging period. Have the authors found a solution to this difficulty?

The elimination of chimneys will necessitate the provision of additional means of ventilation if floor warming is not to be blamed for stuffy conditions.

Have the authors any experience of the generation of static electricity causing shock owing to the excellent insulating qualities of warm carpets? Three cases have come to my notice recently during conditions of low relative humidity, and the phenomenon can be quite alarming.

Mr. A. J. Mare (*at Birmingham*): The authors mention that, with a substantial type of building, a 12-hour on-off period of heating will keep the building warm. Presumably the domestic house has insufficient thermal capacity for this type of heating, which raises the question whether the authors have tried a 12-hour charge with a domestic establishment using double glazing of the windows and thermal insulation of the ceiling upstairs.

With reference to the industrial or commercial use of floor warming, where there is an e.h.v. supply and the consumer is charged on maximum demand during the day-time, if his office block is not of sufficient thermal capacity and he installs off-peak floor heating, he will need supplementary heating during the day, which will increase his day-time maximum-demand charge. Under these circumstances, it would seem that, to be of use to the consumer and the supply undertaking, the system must work on a 12-hour charge. In some cases this is done with a mixture of floor warming and thermal-storage block heaters. On a first or second floor, where there is even less thermal capacity, one presumes that the authors would use an even larger proportion of block heaters than on the ground floor. A worse case of the first or second floor is where there are anti-noise devices consisting of glass wool laid between the screed and concrete beams, so that the heat cannot get downwards into the concrete structure and can only be stored in the screed. Under these circumstances, can the authors state whether there is any possibility of doing without the midday boost?

Mr. R. Yorke (*communicated*): The off-peak tariff is the key to the economic operation of electrical floor warming, since it is basically a thermal-storage device. The South of Scotland Electricity Board offers extremely attractive off-peak tariffs, with the result that the electrical method of heating is competitive. In the south of England, however, the Southern Electricity Board offers an off-peak tariff which is virtually useless so far as the domestic consumer is concerned. A consumer would have to use something like 9 MWh per quarter even to begin to make a saving on the meter and time-switch hire charges. This is something like five times greater than the average quarterly consumption for domestic premises. With reference to Section 5.2.3 of the paper, where a figure of £40–45 is given as the annual cost of floor warming and water heating, the Southern Electricity Board tariff would give a cost for the 11MWh alone of about £50, and, together with water heating, the annual costs would be £80 or more. However, I do not think that the cheapest form of heating is necessarily the best, and I have installed what may be the smallest floor-warming system in the country. This is in my own kitchen and it has a loading of 350 watts. I decided on this form of heating after first reading the paper, and am extremely satisfied with it.

The authors state that a floor covering of almost any material has no effect on the heat dissipation from the floor. How does this differ from the application of thermal lagging to a hot-water cylinder, where considerable reduction in heat losses can be effected by quite simple lagging?

Mr. S. Scholefield (*at Stoke-on-Trent*): In this particular Sub-Area we have connected, in the last two years, 286 kW and 542 kW, respectively, and we have also connected over 1 100 kW of block storage.

During the year 1956–57 approximately 1 MWh was used for storage heating and approximately 3 MWh in 1957–58—an increase of over 200% on the first two years. From this, some appreciation of the rate of growth of this load can be assessed.

In this Sub-Area we are more attracted to the solid p.v.c. type of installation, mainly, of course, because it is the cheapest. Cheapness in this case does not necessarily mean nastiness. If we can fit and forget this type of installation it would be a very fine thing indeed. In my own home, which was recently built, I have installed some 12 kW of floor heating, solidly embedded, and of this I am using 9 kW, the other 3 kW being spare circuits which were laid in case of failure. However, if this failure is brought about by subsidence or cracking, I have no doubt that the spare circuits will fare just as badly as the circuits being used. I can speak very highly of the comfort conditions engendered in floor warming, and, in addition, the drying out of the premises was infinitely faster than would

normally have been the case. I have not yet completed a full year's use, and so it would be unreasonable to attempt to give a firm estimate, but I am quite happy about the cost and I think it is well worth the comfort conditions attained.

We have some flats in this area, but, unlike those mentioned in the paper, they have only three storeys. We rather envy the 7- and 11-storey types where a number of floors are sandwiched, but subsidence problems in this area preclude this weight of building. There is no doubt that, in the 3-storey flat, the rate of consumption in each floor does show a marked difference and seems to average a ratio of 1 (ground floor): 0·8 (1st floor): 1·3 (2nd floor).

I agree with the authors that night storage, taking advantage of off-peak tariffs, is a load that will develop, and there is every indication that it will be possible to hold the off-peak tariffs for some considerable time to come. In fact, present indications are that tariffs could tend to become more favourable to night storage.

We are introducing a new conception of heating in residential, commercial and industrial premises, and this requires a new conception of architecture. Tremendous savings are possible in the design of buildings without flues, but a great deal of care has to be devoted to the heating properties of building materials. A light type of structure will not have enough thermal capacity for satisfactory heating, and similarly, too heavy a structure could absorb heat *ad infinitum*. A balance has to be struck between these types, and a sound study of thermal insulation must be made. I appeal to any architects or builders to take this matter of storage heating very seriously, since I am sure that it has a tremendous future and will affect the building industry to a great extent in the future.

Messrs. J. W. Moule and **W. M. Stevenson** (*in reply*): In view of the large number of contributions, the many points raised and the fact that several persons often made the same point, individual contributors are not referred to by name.

Heat Flow from Warmed Floors—Thermal Insulation.—It is agreed that, given a dry site, thermal insulation underneath the whole of the concrete floor is unnecessary and indeed can be a disadvantage in that the subsoil is not available for additional heat storage. In these circumstances the fringe insulation shown in Fig. 11 is recommended. Full thermal and damp insulation giving a 'tanking' effect is, however, necessary if the site is inherently wet.

When the provision of fringe insulation is particularly difficult, as in the case of the building constructed on a concrete raft, the cost may not be worth while, having regard to the relatively small savings in annual consumption.

With multi-storey flats, insulating material usually covers the whole of the floor area, giving sound as well as thermal insulation. The insulating material is turned up at the perimeter of the floor and prevents loss of heat into the main walls of the building.

Floor Surface Temperatures.—The limitation of the floor temperature to 73° F relates to average temperatures between 'charging' cycles. The temperature may be somewhat higher immediately after switching off the supply and will fall slightly until the supply is re-established. No discomfort is experienced if the average temperature during this period does not exceed 75° F.

Floor Coverings.—When a warmed floor is covered by a carpet the temperature of the concrete builds up until a sufficient temperature difference is created between the underside and the surface of the carpet to permit passing the necessary amount of heat to warm the room until the room thermostat operates. With a hot-water cylinder, the temperature of the water is controlled and the lagging is, of course, a much better thermal insulator.

With regard to the generation of static electricity in carpets, this has nothing to do with floor warming except in so far as the carpet is thereby kept free of moisture.

Building Heat Loss.—Details of the thermal properties of building materials can readily be found in Reference 6.

Electrical Loading and Seasonal Electrical Consumption.—Questions raised about these sections of the paper bring out the fact that, on both counts, an electrical floor-warming installation gives better results than would be expected from conventional heating calculations. The only ready explanation is that the present general approach to heating problems has been built up on long experience with orthodox heating systems, and the entirely different characteristics of floor warming need quite a new outlook. There can be no gainsaying the fact that, in general, the results from floor-warming installations have been better than would have been expected from original estimates of the performance.

Floor warming is able to meet an exceptionally cold period, as the heat stored in the floor would provide any extra warmth required if the daily heat requirements exceeded the maximum daily heat input.

Control.—Internal thermostats are always necessary in order to fix the general level of warmth required in the particular space of the building. Thermo-time regulation can also be justified, except with quite small buildings, as the additional cost is quickly repaid by annual savings in electricity consumption. Without the minimum input of four hours recommended in the paper, there is a danger that the floor might, during warm weather, gradually lose its store of heat and be unable to meet a sudden spell of cold weather.

Undoubtedly, the use of supplementary heating in dwelling houses can complicate the control problem, since it may postpone the switching of the floor-heating thermostat with the result that the floor is unable to obtain a sufficient heat input during the night. Electrical supplementary heating is not a great problem, but a solid-fuel fire with its resultant heating of the fireplace and surroundings can have the effect of delaying the switching in of the floor heating until well into the night.

Types of Electrical Floor Warming.—A considerable number of contributions were made to this section of the paper, most being requests for further information.

(*a*) Heating cables used in metallic tubing are usually of the 'twin-core' type with the remote ends connected. This obviates any inductive effect either in the tubing or the expanded-metal heat diffuser.

(*b*) The use of very dry mix is always preferable and is essential if the maximum mechanical strength of the floor is important. There is no appreciable difference in the laying time of the screed itself or in the subsequent annual electricity consumption, although less electricity would be used for drying out the screed.

(*c*) An earthed screen over a p.v.c. cable is usually required by the Factory Inspector for buildings subject to the Factory Regulations.

(*d*) In our view, a heat diffuser is effective in securing uniform transmission of heat through the concrete screed, and therefore a uniform floor surface temperature. As the distance between adjacent cables is reduced, the need for a heat diffuser is lessened.

Particulars of Some Actual Installations.—So far, we have experienced no difficulty in fixing machinery in factories employing floor warming. Except for very heavy machines it is unusual for factory floors to be broken, as pads and adhesives make this unnecessary. In any event, large machines require special foundations, and the layout of the floor-warming installation can be designed accordingly.

Moreover, no difficulty has been experienced from the entry of vermin into floor-warming troughs and ducts. This should be impossible if the installation is carried out with reasonable care.

With regard to multi-storey flats, the relatively small amount of concrete in the intermediate floors renders a midday boost essential if comfort is to be maintained during the afternoon. The heavier the construction, the more likely is the building to have good thermal characteristics. However, the present trend of building construction, unfortunately, is to err on the light side, and, in consequence, care must be taken to ensure adequate insulation to counteract excessive heat loss from modern types of buildings. Water heating operates quite satisfactorily on an off-peak tariff with a midday boost, and, although this might lead to some increase in the demand experienced in the evening, it is not a serious matter for the Area Board compared with the possibility that, if unrestricted in use, the water heaters would add substantially to the maximum demand.

With two-storey dwellings, a really warm hall on the ground floor undoubtedly helps to provide some warmth throughout the upper floor. Floor warming could be installed in a wooden first floor, but, as bedrooms are usually involved, it is not generally regarded as worth while.

Tariffs.—Several questions about Area Board tariffs and the C.E.G.B. bulk-supply tariff should be directed to the particular Area Board concerned. Undoubtedly, a low differential between the follow-on rate of the standard domestic tariff and the off-peak tariff militates against the development of floor warming in dwelling houses, but even a 20% differential makes it worth while if 'full house' floor warming is in mind.

As with multi-storey flats, a midday boost is essential for the average dwelling house in view of the smaller amount of concrete in the floor compared with a heavier building.

Economics of Electrical Floor Warming as compared with other Heating Systems.—Several contributors referred in some detail to Table 2, criticizing some of the figures brought out. In comparing tons of coal or oil with kilowatt-hours of electricity, it must be remembered that:

(*a*) Electricity is applied at the point where the heat is required, whereas with boiler installations the hot water or steam has to be transmitted from the boiler house to the point of application.

(*b*) The total heat input to the building with floor warming is appreciably less than that required with conventional heating systems. A lower air temperature will provide equivalent comfort conditions, and moreover, owing to the even lower average air temperature, the building heat loss is reduced with floor warming.

(*c*) In calculating boiler efficiencies, insufficient attention is often paid to the fact that the efficiency in question is the average operating efficiency of a boiler throughout the full year. This must be appreciably lower than the test efficiency, particularly when regard is paid to the fact that the boiler plant has to operate under reduced loadings during the summer months.

We provided the footnote to Table 2. The calculations on the right-hand side were, as stated, compiled by an architect.

Reference was made in the discussions to the importance of taking a forward view when deciding on the method of space-heating a building. In this connection it was suggested that, with the advent of the nuclear power station, the costs of off-peak electricity would become more favourable in comparison with other fuels. We fully support this point of view, and undoubtedly, if those responsible for new buildings endeavoured with open minds to take account of the possibilities, say, 20 or even 10 years hence, there can be no doubt that electrical floor warming would rapidly take its place as the principal method of space heating in new buildings.

DISCUSSION ON 'EARTHING OF LOW- AND MEDIUM-VOLTAGE DISTRIBUTION SYSTEMS AND EQUIPMENT'*

Before the Northern Ireland Centre *at* Belfast 9*th December*, *the* Irish Branch *at* Dublin 11*th December*, 1958, *a* Joint Meeting *of the* Western Supply Group *and the* South-Western Sub-Centre *at* Plymouth 16*th April*, *and the* Sheffield Sub-Centre *at* Sheffield 20*th May*, 1959.

Mr. E. N. Cunliffe (*at Belfast*): The author has made out a good case for protective multiple earthing, but it would seem that the separate-earthwire system would be even better were it not for the extra cost of the additional conductor and the possibility of its breakage. These two disadvantages are important in extensive l.v. distribution systems, but it should be remembered that quite a large part of our rural development is now taking place using single-phase h.v. distribution with small transformers installed very close to individual consumers. In such cases the separate-earthwire system would appear to be an attractive one, since the extra conductor, being extremely short, would cost very little. Moreover, the risk of a broken earth return could be practically eliminated by bonding it to the neutral at either end, so forming, in effect, a small p.m.e. system with duplicate neutral.

Since this danger of a broken neutral conductor is the main risk with p.m.e. systems, there are also other measures which could be taken towards an improvement. For instance, all service neutrals could be duplicated. At the same time, consumers' earth-continuity conductors could be arranged in the form of a ring main at little extra cost, so that a single break would not affect continuity. Also, in a comprehensive overhead distribution scheme it may be possible to join together the neutral conductors at the far ends of adjacent radial distributors in favourable cases.

Mr. E. S. Ritter (*at Belfast*): Any protective system should provide an indication of when it has operated and when the operating conditions are faulty. The latter condition is not always met in rural areas, and some form of periodical check test by the supply authority is indicated.

Why are differential-current earth-leakage circuit-breakers not in general use? This would seem to be the ideal protective method. Where single-phase transformers are connected across two phase wires of the h.v. system, should an electrostatic earthed screen be placed between the two windings to prevent a capacitance current flowing to earth through the l.v. earth connection? There is a voltage of 0·58 times the h.v. phase voltage across the two windings. Has sufficient thought been given to

* Mather, F.: Paper No. 2420 S, October, 1957 (see 105 A, p. 97).

the advantages of single-phase 3-wire distribution for feeding a number of consumers along a road with a balancing transformer at the end? The addition of one conductor will halve the voltage drop, and the neutral can be broken without appreciably altering the neutral-to-earth or the appliance-to-line voltage. One of the live conductors could break, and, except for the leakage to earth of the broken end, the supply conditions would remain; only if both a neutral and a live conductor were broken would difficulty arise. If desired, the line could be fed with power from both ends, in which case both transformers would act as balancers; in addition, a balancing transformer could be placed at the half-way point.

Mr. W. Szwander (*at Belfast*): The subject of adequate protective measures to be adopted for preventing dangerous voltages on metallic surrounds of electrical apparatus is one of the oldest controversies still not finally settled—as is proved by numerous discussions and publications still appearing on the matter. Of the original alternatives, the application of insulation is now limited to the replacing of metallic surrounds by insulated materials; protective circuit-breakers, owing to their cost and the considerable maintenance required, are limited to special cases where both excessive voltage to earth and leakage current must be limited; earthing appears to be the most satisfactory measure and has become most widely used, but there are circumstances when it cannot be successfully (and economically) applied; such difficulties are also expected to increase in the future, with the growing use of insulated water pipes and plastic-sheathed electric cables. The combination of earthing with neutralizing, in the form of protective multiple earthing, appears to be the only possible solution in many difficult cases. The outcome will not be one prescription for all cases, but judicious application of the right measures for each set of individual circumstances. On the other hand, I can see only advantages arising from applying p.m.e. where earthing has so far been chiefly used, e.g. in underground networks, where each consumer could be requested to provide his own earth (as good as can be easily obtained), but his earth-continuity lead and the earth connection would be connected to the service-cable neutral conductor, as well as to the metallic protective sheath. The use of the neutral conductor inside each consumer's installation in the place of the earth-continuity conductor is a matter also deserving serious consideration, since it can result both in savings and in an increase of the general safety standard.

Co-ordination is essential between safety measures undertaken in the supply system and the consumer's installation, and while this is by no means an accepted practice, it should be the supply authority's responsibility to give every consumer access to a terminal for connecting his earth-continuity conductor, such terminal being either a plain earth terminal or a neutral-connected terminal when p.m.e. is used. While a supply authority would naturally satisfy itself as to the effectiveness of the measures adopted, a form of indemnity, either through suitable legislation or through proper wording of supply agreements, would probably be desirable.

Mr. N. C. C. De Jong (*at Belfast*): The Post Office is interested in p.m.e. because earth signalling is used on some of our overhead lines and the field caused by varying currents in the neutral can give rise to interference. Our experience of the system, however, has been most encouraging, and we should like to see it adopted generally. We use earth-leakage circuit-breakers in those telephone kiosks which are supplied from overhead mains. In this case, the generally low resistance offered by the kiosk itself and its connection by our own wires to exchanges may not allow us to adopt p.m.e., but tests are being made to determine the risk involved. Reference has been made to the use of earth strips laid at shallow depths. The Post office considers deep-driven rods to be more economical and certainly more effective where they penetrate beyond low-water level.

Mr. W. H. English (*at Belfast*): The maximum test currents mentioned in the paper are those corresponding to 3 and 6 kW loads. It would be interesting to know the rating of the largest fuse protecting any consumer's installation connected to a p.m.e. system of the types described.

What would be the maximum current-carrying capacity of the earthing leads and earth electrodes at the various premises described, and would this capacity be sufficient to cope with the maximum current permitted by the consumer's main fuse? Would the resistance of the earth loop remain constant or vary with the current flowing?

If a phase-to-neutral fault occurs on the distributor, there will surely be a danger of a momentary rise in voltage at points along the neutral conductor and hence in all earthed metalwork. Would not such instantaneous voltages be dangerous in most instances?

Mr. R. A. H. Jackson (*at Dublin*): Until electricity supply came to be extended beyond the limit of municipal water mains, highly satisfactory earthing was readily available for the class of consumers covered by the paper. Indeed, it was so good that a broken neutral connection in the service or installation might remain unnoticed until tragically revealed when a plumber cut the pipe.

However, the problem of earthing became urgent when supply began to be extended into rural areas, where direct earthing generally meant connecting the earth-continuity conductor to an earth electrode provided by the consumer and having a resistance exceeding 50 ohms. It was thought that the difficulty of effectively guarding against shock and fire would be secured by the use of earth-leakage circuit-breakers. In practice, however, it has been the experience that these fail, owing to the mechanism sticking and the coil burning out. Lightning also caused coil failures, and making the neutral the top conductor in overhead networks did not eradicate this weakness. In consequence, p.m.e. has been coming into favour and much has been written on the subject. The real merit of the paper lies in the record of field tests on rural networks. These have demonstrated that the safety secured by p.m.e. was better than theory would suggest; this evidence and the apparent unfounded fear of broken neutrals advance the claims that have been made for it. However, experience has shown that:

(*a*) Weak connections which could cause an open-circuit can occur, and this and other considerations would suggest that there should be two connectors or preferably a compression connector, suitably weather-proofed where necessary, at every joint in the neutral up to the consumer's meter.

(*b*) There should be no delay in the protecting fuse blowing for a short-circuit at any point right up to the meter.

(*c*) Reasonably good, secure and approximately equal earthing of the neutral should be made before the first consumer of, and at the end of, all overhead networks.

(*d*) There should be some evenly distributed neutral-conductor earthing between these points.

(*e*) Ordinary direct earthing to an electrode or metal water piping, at each consumer's premises where 'earthing' is necessary, should be joined to the neutral.

The danger of a high voltage appearing on the neutral due to a breakdown of insulation on the h.v. side at a transformer site is not realized where the h.v. star point is not directly earthed.

The fire risk of 'earth' faults is not covered in the paper, and under certain conditions with a neutral break it could occur that an earth-continuity conductor could come into circuit to carry current above its safe capacity.

Mr. H. Montgomery (*at Dublin*): At the inception of the rural electrification scheme in 1946 we used earth-leakage relays everywhere, since direct earthing was impossible. These proved

unreliable, and tests taken in rural areas showed an average of 25% inoperative. Furthermore, the first cost of the relays was a deterrent to the provision of socket-outlets, and consumers were in many cases wiring for lighting only. Cattle were being killed by step voltages at earths, caused by persistent earth faults which defective earth-leakage relays failed to clear. (As a protection against step voltages all earths are now insulated for 12 in above and 18 in below ground.) In 1954 we adopted p.m.e. which we called 'neutralizing.' It was appreciated that this did not give 100% security, but it gave a high degree of security which was lacking with earth-leakage relays. Since then we have connected about 120 000 consumers, all of whom are in p.m.e. areas.

Experience of p.m.e. has been satisfactory, the only recorded cases of shocks due to it occurring where the phase and neutral were inadvertently interchanged at a pump motor and the earth-continuity conductor had not been extended to the motor, but the motor body had been earthed to the neutral. In this country the 'handyman' electrician is a risk which has to be reckoned with in rural areas.

The paper brings out the importance of having a consumer's earth electrode as security against a broken neutral, and this is now required by the Electricity Supply Board in p.m.e. areas.

Why was 10 ohms chosen for the maximum permissible earth resistance for p.m.e., and what is done where it is not economic to achieve this value?

Why has the North Western Board not made it obligatory for consumers to provide an earth electrode?

Mr. M. G. Byrne (*at Dublin*): In Fig. 7 it might have been interesting to have voltage readings for Chadderton Heights farm had the break in the neutral been made between Chadderton Heights and Nod farm.

In the Dundalk district, p.m.e. had been found to be a very satisfactory answer for small villages recently connected to public water mains, where it was not found economical to reduce the mains neutral earth to a figure suitable for direct earthing.

Mr. B. Macquillan (*at Dublin*): In the country areas of Ireland the 10 kV neutral is unearthed (except through a voltage transformer for earth-fault signalling). The earth-fault current at a rural distribution transformer is thus limited to a capacitive current of about 5–15 amp, which would cause on an adjacent l.v. neutral earth only a small fraction of the voltage rise which would occur had the 10 kV neutral been solidly earthed. The substation frame and l.v. neutral earths may thus be closer together without danger. Some telephone interference has been experienced in the past in this country with the l.v. neutral earthed at more than one point. At heavy load periods the voltage drop along the l.v. neutral conductor becomes, with multiple earthing, a voltage drop along the ground. With a telephone subscriber and the telephone exchange located close to the two different neutral earths, sufficient potential is available to ring the subscriber's telephone bell when the exchange is using the central-battery signalling system. The trouble disappears when the exchange is changed to a more modern system.

Mr. T. McKenna (*at Dublin*): Up to 1954, p.m.e. was permitted in this country, provided that an earth resistance of 10 ohms could be achieved. It was seldom, if ever, used. In 1954 the earth-resistance requirement was extended to 50 ohms for networks with less than 50 poles and at least every second pole was earthed. In 1955 the regulations were relaxed and a graded scale introduced with 10 ohms for a 50-pole network, 50 ohms for a 6–50-pole network, 75 ohms for a 2–5-pole network and 200 ohms for a one-pole network with a special earth wire run back to the neutral connected to this special wire. A minimum number of earth electrodes are specified for each type of network. Our procedure now is that the field engineer designs his networks and proceeds as follows:

(*a*) Earths the neutral at all end-poles, and if this does not give the required minimum number of earths, other poles are earthed.
(*b*) If the earth resistance is below the specific value, the network is passed: if over it, a fixed amount of earthing material is added.

This procedure simplifies the work for the engineer in the field, saves time, reduces cost and, we feel, gives as safe a network as it is economically possible to get.

I should like to know whether the 10 ohms presents a stumbling-block to p.m.e., for I am sure that the country south of the Scottish border, around the Lake District and in the Pennines, is similar to ours.

Mr. A. F. Kelly (*at Dublin*): Protective multiple earthing provides a very good level of protection, but it is very necessary for the consumer's installation to be properly wired. In this respect, do the North Western Board permit isolated sections of an installation to be bonded to the neutral at their feed points, or is it necessary to run an earth-continuity conductor back from each section to be bonded to the neutral at the service position?

Mr. J. W. O'Neill (*at Dublin*): Since the consumer's earth-continuity conductor is solidly connected to the neutral, why provide this third conductor rather than connect the frame earth to the neutral at each piece of equipment?

Mr. E. V. Cleary (*communicated*): The author's recommendations on the earthing arrangements for indoor-type distribution stations in cities would be of interest, particularly in relation to the metalwork of h.v. switchgear, the l.v. board, the transformer tank, the l.v. neutral, and cable sheaths. How are these recommendations affected if the system is operated with the h.v. neutral insulated and if the l.v. system is partly underground and partly overhead?

Mr. T. G. Ward (*at Plymouth*): I note that there are a considerable number of p.m.e. systems with only one consumer. A useful arrangement would appear to be to earth the neutral at the consumer's meter position only. This is not p.m.e., and it is unnecessary to get the earth resistance down to 10 ohms. The only purpose of the earth connection is to ensure blowing of the 11 kV fuse if an h.v./l.v. fault develops in the transformer winding, for which a value of 50 ohms has been found acceptable. Breakage of the l.v. neutral merely interrupts the supply and does not cause a dangerous condition.

I disagree with the author's dismissal of direct earthing using overhead earth wires. The simplest and cheapest method of providing earth electrodes on p.m.e. systems is to bury a galvanized-iron earth rod in the pole hole. Tests made on a large number of such rods indicate that the average resistance is about 60 ohms. An l.v. system of some six or seven poles is therefore required to obtain an overall resistance of 10 ohms. The cost of improving this earthing on small systems of up to, say, four poles appears to favour the use of a direct overhead earth wire.

Another matter which can cause difficulty is in the testing of consumers' earth-continuity conductors. The p.m.e. regulation says that each circuit must be tested with 10 amp for 5 min. The recent requirement of The Institution's Wiring Regulations for earth-loop testing has resulted in a crop of instruments being available, very few of which are suitable for testing installations on p.m.e. systems, because either the rating is inadequate or the circuit unsuitable.

Mr. L. H. Shelley (*at Plymouth*): Table 4 indicates a tendency for earth resistances to increase, and the dates given (1953 and 1957) suggest a definite upward trend in the majority of the positions. Were any particular steps taken to mitigate this, such as the use of the chemically treated clay put forward as being of great value in reducing earth resistances? Values were presumably checked between 1953 and 1957: was any definite reason for the increases ascertained, and did extraneous condi-

tions, such as weather or any other feature, have any bearing on the results?

Another important point which may be of some value in the efficacy of p.m.e. is that each earth lead on a consumer's installation should be brought separately to the earth point of the overhead service. The earth of a particular circuit has been known to be broken, thereby placing some of the installation in jeopardy. The extra cost of doing this is small compared with the increase in safety derived.

The economic considerations of an overhead rural scheme now proposed mean that, with the scattered position of most of the farms and dwellings, it is more advantageous to extend the h.v. system and have small transformers for all premises. Arising out of this, therefore, it would appear that p.m.e. cannot be so useful and its use is therefore likely to wane. I should like the author's opinion on this point in so far as the economic radius of l.v. lines is now somewhat limited to 100 yd or so, bearing in mind voltage drops and all the necessary details which have to be observed.

Mr. W. R. Rowe (*at Plymouth*): It is understood that the North Western Board's resolution in 1953 regarding earthing refers only to new consumers, and to certain other cases where an extension of the consumer's installation has been undertaken. In the South Western Board's Area the majority of new rural consumers are being connected by p.m.e. installations, where, in effect, an earth terminal is provided; and in urban areas, where our underground cables are lead-sheathed and plumbed, an earth terminal is also available, subject to an indemnity.

In effect, therefore, the policy adopted by the North Western Board would not appear to be quite so all-embracing as at first sight. What is the proportion of consumers whose earthing responsibilities are now undertaken by the Board (and in the intervening 5½ years), and are there any proposals for dealing with much larger proportions who still appear to be responsible for their earthing arrangements?

Mr. H. Anderson (*at Sheffield*): The author calls attention to the fact that, with a broken neutral on a p.m.e. system, the voltages measured are not so great as might be expected, because the potential of the fabric of the building rises. Almost the same state of affairs arises with an uncleared fault on a directly earthed system. I once collected data of 64 cases of shock suffered by electricity consumers in a poor earthing area, and in none of these was anything worse than inconvenience suffered. Indeed, in one instance a consumer had suffered shocks for some time without having done anything more than binding all his taps with insulating tape. In such instances with direct earthing there is something to be said for bonding together all metalwork in the proximity of the installation. The trouble occurs when one attempts to get outside of this 'Faraday cage'.

Attention has been paid by some Area Boards to installing small circuit-breakers in place of the usual service fuses. Such circuit-breakers are now becoming competitive in price when h.b.c. fuses may have to be renewed. There would appear to be particular advantage in using them in rural areas, where distances are considerable and premises are relatively inaccessible for the replacement of blown service fuses. It would not be a difficult matter to fit them with a voltage-operated earth-leakage trip coil, and the whole unit would be on the supply side of the meter and under the control of the supply authority. Several modern types of leakage trip are provided with lightning protection, which is one of the hazards to which these devices are particularly prone. The additional cost of the overload and earth-leakage-trip circuit-breaker would be partly offset by crediting the cost of supply authority fuses.

When a consumer unit of the E.D.A. type is used in a rural area, the double-pole main switch usually fitted can be omitted and replaced by a double-pole leakage trip, which is about the same price as the main switch.

The relaxed p.m.e. regulations require that, except in a system with a single distributing main, no linked switch shall be fitted in any main. Can the author explain what is meant by this? It is not usual to fit a switch in a distributing main, but does this imply that only single-pole switches are to be employed if this is done?

Does the author advocate bonding of gas pipes to the protective metalwork and the neutral? This would appear to be necessary if the whole building fabric is to rise in potential, and it also appears to be necessary under the p.m.e. regulations, since it is almost certain to be near the electrical installation. I can foresee a danger of a fire risk, however, if the gas pipes are bonded in.

The author is not quite fair in saying that under broken-neutral conditions the shock risk will be less than with other methods of earthing commonly used. Shocks will arise with other methods of earthing (ignoring direct earthing) only if a breakdown of the system occurs as well as a faulty appliance. With p.m.e., however, shocks of some kind will be experienced by all consumers on the system who have cause to handle their apparatus, without any apparatus fault, if neutral discontinuity arises. The author has made his point by stressing that with careful design the chances of a neutral breakage are extremely unlikely.

Mr. F. Mather (*in reply*): *Mr. Cunliffe.*—Where a transformer supplies an individual consumer there is no need to provide a separate earth wire. Earthing of the neutral at the consumer's premises only is a safe and economical arrangement. Experience shows that the risk of neutral breakage is small and the p.m.e. regulations provide a high standard of safety without duplication of conductors.

Mr. Ritter.—Differential-current earth-leakage circuit-breakers are not in general use because simpler, cheaper and more compact equipment is usually adequate.

Mr. Szwander.—It will be surprising if the use of p.m.e. does not extend into underground networks, as it has abroad, and I agree that appreciable economies can result in consumers' installation wiring.

Mr. De Jong.—It is useful to have further confirmation that the Post Office do not find p.m.e. objectionable.

Mr. English.—In general, the service fuse will have a rating of 60 amp and the largest consumer's fuse 30 amp. The rating of a 7/·044 earthing lead is approximately 900 amp for 1 sec and 400 amp for 5 sec. The current-carrying capacity of earth electrodes is never a limiting factor in this application, and the resistance of the earth loop is unlikely to vary appreciably with the magnitude of current involved.

With a phase-to-neutral fault on the distributor the fuses would blow quickly. There would be a brief elevation of neutral voltage, but this could not exceed 120 volts and would generally be much lower. The measurable shock voltage would be unlikely to exceed half the calculated figure.

Mr. Jackson.—It seems unlikely that trouble will be encountered due to earth-continuity conductors being overloaded.

Mr. Montgomery.—The choice of 10 ohms as the maximum resistance of the neutral to earth was partly the result of a statistical analysis of shock risk and partly to ensure that the high-voltage protection would operate for faults between h.v. and l.v. windings of transformers. It is not usually difficult or costly to achieve a figure of 10 ohms, but in rare cases the use of a continuous earth-wire or earth-leakage circuit-breakers might be justified.

An Electricity Board is not entitled under the Protective Multiple Earthing Regulations to require a consumer to provide an earth electrode. Nevertheless, an electrode in some form, e.g. a water pipe, is often available.

Mr. Byrne.—The cost of reducing neutral-point earths to a

value suitable for direct earthing can be considerable, and the choice of p.m.e. in the circumstances described seems a wise one.

Mr. Macquillan.—Several telecommunication engineers have now confirmed that telephone interference has been reduced after the adoption of p.m.e.

Mr. McKenna.—Until recent years the British p.m.e. regulations required an overall resistance from neutral to earth of not more than 2 ohms, with electrodes not exceeding 4 ohms and 10 ohms respectively at stipulated positions. The relaxation to 10 ohms has largely eliminated the difficulty.

Mr. Kelly.—The consumer's earth-continuity system is carried to the service position and connected to the neutral at that point only.

Mr. O'Neill.—The Institution's Wiring Regulations require an earth-continuity conductor but, as an alternative, permit earthed concentric wiring on p.m.e. systems.

Mr. Cleary.—In city distribution systems, no adverse experience has been reported to me resulting from common bonding of h.v. and l.v. switchgear, transformer, h.v. and l.v. cable sheaths. I have had no recent experience of operating with the h.v. system neutral insulated.

A relaxation of the British regulations permits the use of p.m.e. subject to certain conditions, on overhead branch lines from underground systems with normal earthing.

Mr. Ward.—There may be a few cases where a continuous earth-wire is slightly cheaper than p.m.e., but generally the latter is much more economical and has points of technical superiority. Simple equipment suffices for the test of the consumer's earth-continuity conductor.

Mr. Ward's point about the single consumer is agreed; p.m.e. was used in a few such cases for purposes of comparison.

Mr. Shelley.—No general upward trend has been reported in the overall resistance between neutral and earth on p.m.e. systems. Despite the tendency to limit the length of l.v. lines, the average number of consumers per transformer is four or five. The use of p.m.e. in such circumstances is economical and technically sound.

Mr. Rowe.—Figures are not readily available for the number of consumers using the Board's earthing facilities. Several of the larger authorities offered similar facilities, either in whole or in part, for about ten years prior to nationalization. When the earthing arrangements of existing consumers are found unsafe (e.g. owing to the use of non-metallic pipes by the water authority), it is generally possible to reach some mutually satisfactory solution.

Mr. Anderson.—In a system with two distributing mains, the earth at the transformer may be omitted, since there are others at each side of any possible neutral break. A switch in the neutral of either line would then be unsafe.

Bonding the gas pipes is implicit in the regulations and should reduce rather than increase the fire risk.

With a properly designed p.m.e. system the shock risk is small, even with a broken neutral. If a continuous earth-wire breaks, there is not normally the advantage of distributed earths, and the shock risk may be serious.

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ABBREVIATIONS

(P)—Address, lecture or paper.
(p)—Subject dealt with in a paper or address.
(D)—Discussion.
(A)—Abstract of paper or address.

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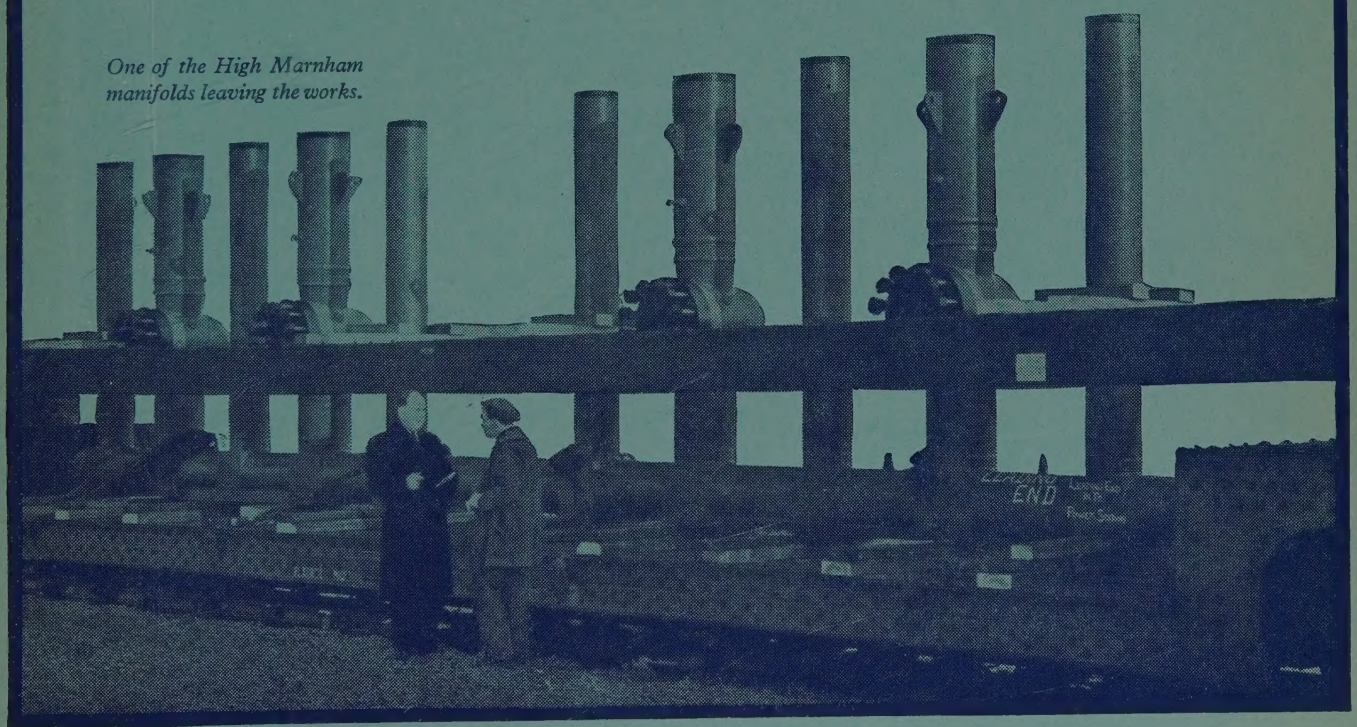
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Members are asked to bring to the notice of the Court of Governors any deserving cases of which they may have knowledge.

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